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Report 862-4

PHYSIOLOGICAL AND PATHOLOGICAL EFFECTS OF
MECHANICAL VIBRATION ON ANIMALS AND MAN

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On: PHYSIOLOGICAL AND PATHOLOGICAL EFFECTS OF MECHANICAL VIBRATION ON ANIMALS AND MAN

Report covers the period: 1 July 1960 - 31 August 1961

Submitted by: William F. Ashe, M.D., Department of Preventive Medicine

Date: September 1961

SUMMARY

This report covers the final 14 months of an initial 36-month study and is made up of the following sections.

Section I. Rat Studies

A. Metabolic and Growth Responses of Unrestrained Rats to Repeated Exposures of Vibration

B. Effects of Vibration on Pregnant Rats

Section II. Dog Studies

A. General Responses of Dogs to Whole-Body Vibration

B. Blood Pressure Responses to Whole-Body Vibration in Anesthetized Dogs

C. Blood Flow in Arteries of Vibrated Animals

Section III. Human Studies

A. Human Psychomotor Performance During Prolonged Vertical Vibration

B. Oxygen Consumption During Human Vibration Exposure

C. Respiratory Frequency, Tidal Volume, and Respiratory Minute Volume in Human Subjects Exposed to Vertical Whole-Body Vibration

D. Skin Resistance (Psycho-galvanic Response) During Whole-Body Vibration

E. Body Surface Responses of Standing Male Subjects Subjected to Vertical Vibrations

F. Occupational Raynaud's Phenomena Due to Vibrating Tools

G. Detection, Recognition and Identification of Visual Forms as a Function of Target Size and Whole-Body Vibration

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PHYSIOLOGICAL AND PATHOLOGICAL EFFECTS OF MECHANICAL VIBRATION ON ANIMALS AND MAN

INTRODUCTION

This report covers the period 1 July 1960 to 31 August 1961. Report Number 3, entitled Physiological and Pathological Effects of Mechanical Vibration on Animals and Man has covered the period 1 September 1958 to 30 June 1960. By way of summary, Report Number 3 covered:

I. Rat Studies

- A. Weight loss and body temperature changes in relation to vibration
- B. Oxygen uptake
- C. Growth
- D. Adrenal response
- E. Metabolism of vibrated rats
- F. Effect of vibration on pregnant rats
- G. Lethal levels of vibration

II. Dog Studies

- A. Weight loss, body temperature and blood chemistry
- B. Heart rate and vibration

III. Human Studies

- A. Literature review of hand injury due to power tools
- B. Clinical study of power tool users
- C. Human psychomotor response to vibration

IV. Engineering Aspects

Since that time the studies reported herein have been completed. In this period the following articles have been published:

1. Problems in Instrumentation for Dynamic Subjects. G. N. Hoover and F. R. Johanson. Proc. National Electronics Conf. 16: 659-671, 1960.

2. Some Responses of Rats to Whole-Body Mechanical Vibration, Part I. W. F. Ashe, E. T. Carter, G. N. Hoover, L. B. Roberts, E. Johanson, F. Brown, E. J. Largent. Archives of Environmental Health. 2: 369-377, 1961.

3. Carter, et. al. Some Responses of Rats to Whole-Body Mechanical Vibration, Part II, Metabolic Gas Exchange. Arch. Environmental Health. 2: 378-383, 1961.

Reprints are attached.

The following papers have been submitted and accepted for publication during this report period.

1. T. M., Fraser, G. N. Hoover, and W. F. Ashe, Tracking Performance During Low Frequency Vibration. Aerospace Medicine. (September 1961 issue)

2. J. V. Gaeuman, G. N. Hoover, and W. F. Ashe, Oxygen Consumption During Human Vibration Exposure, Aerospace Medicine.

3. A. D. Catterson, G. N. Hoover, and W. F. Ashe, Human Psychomotor Performance During Prolonged Vertical Vibration. Aerospace Medicine.

4. G. N. Hoover, W. F. Ashe, J. H. Dines, and T. M. Fraser, Vibration Studies III, Blood Pressure Responses to Whole-Body Vibration in Anesthetized Dogs. Archives of Environmental Health.

Papers presented at Scientific Meetings. (may or may not be published.)

1. Problems in Instrumentation for Dynamic Subjects. G. N. Hoover and F. R. Johanson. National Electronics Conference, Chicago, Oct. 10, 1960.

2. Growth and Metabolic Responses of Rats Exposed to Whole-Body Vibration, G. N. Hoover, W. F. Ashe, and L. B. Roberts. American Physiological Society Fall Meeting, Stanford, California, August 23, 1960.

3. Aspects of the Physiological Response to Whole-Body Vibration, T. M. Fraser, G. N. Hoover, and W. F. Ashe. American Physiological Society Fall Meeting. Stanford, California, August 23, 1960.

4. Oxygen Consumption During Whole-Body Vibration Exposure. J. V. Gaeuman, G. N. Hoover, W. F. Ashe. Aerospace Medical Association, Chicago, April 24, 1961.

5. Human Psychomotor Performance During Prolonged Vertical Vibration, A. D. Catterson, G. N. Hoover, and W. F. Ashe. Aerospace Medical Association, Chicago, April-24, 1961.

SECTION I. RAT STUDIES

A. METABOLIC AND GROWTH RESPONSES OF UNRESTRAINED RATS TO REPEATED EXPOSURES OF VIBRATION

Unrestrained rats perform muscular work when exposed to whole-body mechanical vibration (Carter, et al., 3). It seems apparent that this work is related to adjusting the postural muscles in a defensive effort to damp as much of the vibration as possible. The work load has also been demonstrated in terms of weight loss over the period of vibration exposure (Ashe, et al., 1). In this case the amount of weight loss during the exposure was greater on the first day than during the last exposure five days later with 13 hours of vibration intervening. This would indicate that some form of adaptation has occurred. It is not apparent whether the adaptation is physiological in nature or whether the animal has simply "learned" to cope with the situation.

A weight loss also occurs in restrained rats exposed to comparable "intensities" of mechanical vibration (Schaefer et al., 30). In these studies a single exposure was used. A decrease in food intake and fecal output was also observed. There were no changes in water intake or urine output.

If adaptation to vibration environments can occur, the observed changes in food intake should be altered as the daily vibration exposures continue. If this function does not adapt, however, one would expect a severe loss of body weight over a period of time. If young animals were used, growth rate may be altered. The question then becomes, is food intake altered in the unrestrained rat exposed to vibration as it is in the restrained rat? If so, how is this alteration affected by continued daily exposures? And, how is the growing animal affected?

In an attempt to answer these questions, at least in part, the following experiments were conducted.

1. Methods

<u>Phase 1</u>: Six male Sprague-Dawley albino rats were placed in metabolism cages. A one-week period was allowed for the rats to adjust to their new conditions before the experimental period was begun. The rats were equally divided into control and experimental groups. A five day pre-exposure control period was then maintained during which body weight, food consumption, water intake, fecal weight, and urine volume were measured. Fecal water was estimated by drying the feces to constant weight at 105°C. Following the control period half of the group, three animals, was exposed to whole-body sinusoidal mechanical vibration of 20 cycles per second (CPS), 0.25-inch amplitude (0.5-inch peak to peak)

in the horizontal plane. The exposures were for one-half hour each day for seven days. The control half of the group was placed in similar cages near the vibration machine such that noise and housing conditions were almost constant for all animals. The exposure period was followed by a three-day study of the post-exposure recovery period.

Three such studies were completed, two of which are reported in figures to follow and are designated groups M-1 and M-3.

Phase 2: This study was similar in design to Phase 1 with the exceptions as follows. The experimental animals, 12 to a group, began the conditioning period as 21-day-old rats which were bred and reared in our colony. The vibration exposure was begun on the 28th day of life. The vibration exposure was at 15 CPS, 0.25-inch amplitude in the vertical plane, and was given one hour a day for seven days. Although four studies were started in this series, only two were carried to completion because of the large number of fatalities occurring in the experimental groups (three out of six in M-4 and four out of six in M-5).

Phase 3: In this series the growth rate of weanling rats was studied with daily vibration exposures of up to 45 days. Young rats were weaned at 21 days after birth, and each litter separated randomly into control and experimental groups. On the 22nd day of life, vibration exposures were begun and were continued on a five-day week. The experimental and control animals were housed together in the colony. Before the exposure, the animals were weighed and placed in their specific cages as above. Exposures of experimental animals were at frequencies of 5, 10, 15, and 20 CPS in the horizontal plane, and 5 and 10 CPS in the vertical plane. The single amplitude of vibration was 0.25-inch in all experiments. The durations of exposures were one-half, one, two, and six hours per day. In the groups vibrated in the vertical plane, weight loss over the daily exposure period was also measured.

2. **Results**

For comparison purposes, all data presented are expressed as percent difference from the control group. That is, the control value minus the experimental value is divided by the control value to give the relative change based on the control level.

Food intake in the animals vibrated in the horizontal plane shows only random changes. The data for group M-1 (top of Fig. I-A-1) seem to indicate a small decrease in food intake, but this effect could not be seen in group M-2. In both M-6 and M-7, food intake was severely depressed on the first day of vibration, but returns to near normal levels on subsequent days.

Water intake (Fig. I-A-1) again in the animals vibrated horizontally varied randomly. This is also true of the animals vibrated in the vertical plane.

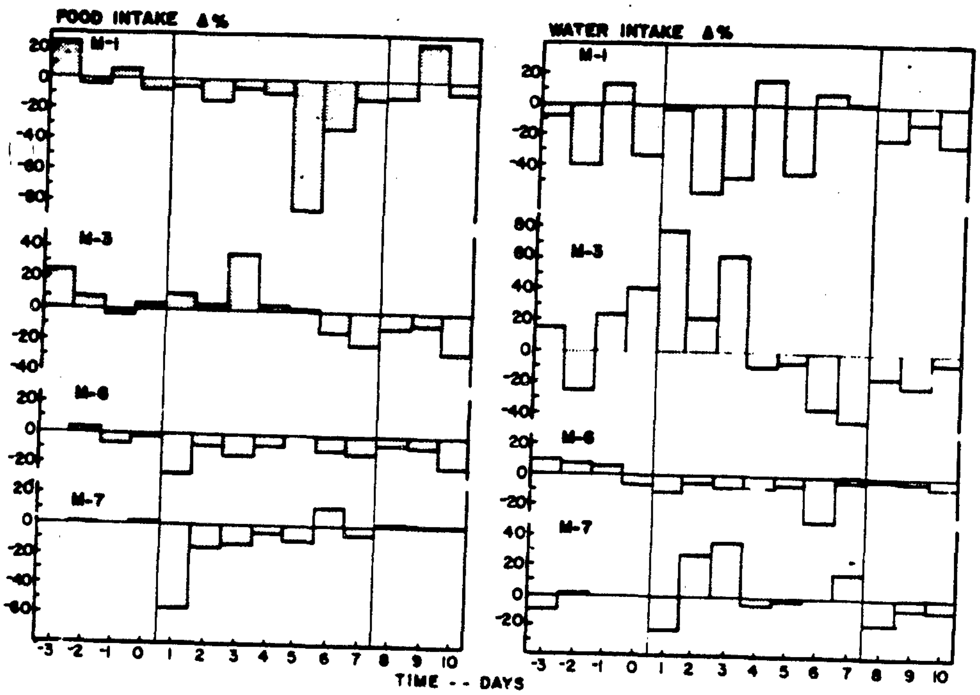


Fig. I-A-1

Total fecal (Fig. I-A-2) output varied randomly in the first four days of studies of M-1 and M-3, with some indication of a depression in the last days of M-3. Significant depression of fecal output occurred in both M-6 and M-7. Fecal water (Fig. I-A-2) content correlates well with the total fecal output in all studies. Body weight on a day-to day basis (Fig. I-A-3) was not significantly changed in any of the Phase 1 or Phase 2 studies. Total water (Fig. I-A-3) output, while significantly changed in specific experiments, seemed to change randomly throughout the studies, and specific changes must be attributed to individual or environmental variables at that time, and not be interpreted as a change induced by vibration.

Dry feces (Fig. I-A-4) in M-1 and M-3 was depressed in the latter half of the exposure period, while in M-6 and M-7 it was depressed throughout. Urine output (Fig. I-A-4) varied randomly.

Growth rates of young rats are given in Fig. I-A-5. In no vibration condition was the growth rate found to be significantly altered. There seemed to be a tendency for growth depression in those animals exposed to vertical vibration, however, this is not statistically significant. The number of animals (N) is given for each condition and refers to both the number of control animals and the number of experimental animals. There were significant weight losses observed in vibrated rats (Table I-A-1) during the exposure period, however, this loss was regained along with the additional weight resulting from growth before the next vibration period began.

3. **Summary and Conclusions**

Food and water balance studies of unrestrained rats exposed to horizontal vibration at 0.25-inch and 20 CPS showed no consistent difference from their control groups. This vibration "intensity" apparently was not sufficient to elicit a response as measured by these crude techniques.

Similar studies in the vertical plane of vibration at 15 CPS (also 0.25-inch amplitude) caused a decrease in food intake and fecal output on the first day of continued vibration exposure. As the daily exposures continued, however, the decrement became smaller as the animal apparently adapted to the conditions. These observations confirm those of Schaefer (30) in restrained rats with single exposures. It would seem that the depressed fecal output is a result of a decreased food intake.

Since adaptation has been shown to occur with respect to weight loss, and now with food intake parameters, it is not too surprising to find that the growth rate of young rats is not seriously affected. Even though there is weight loss during the exposure period and food intake is somewhat depressed, the animal apparently is still taking in enough food to meet the energy requirements plus the amount needed for growth.

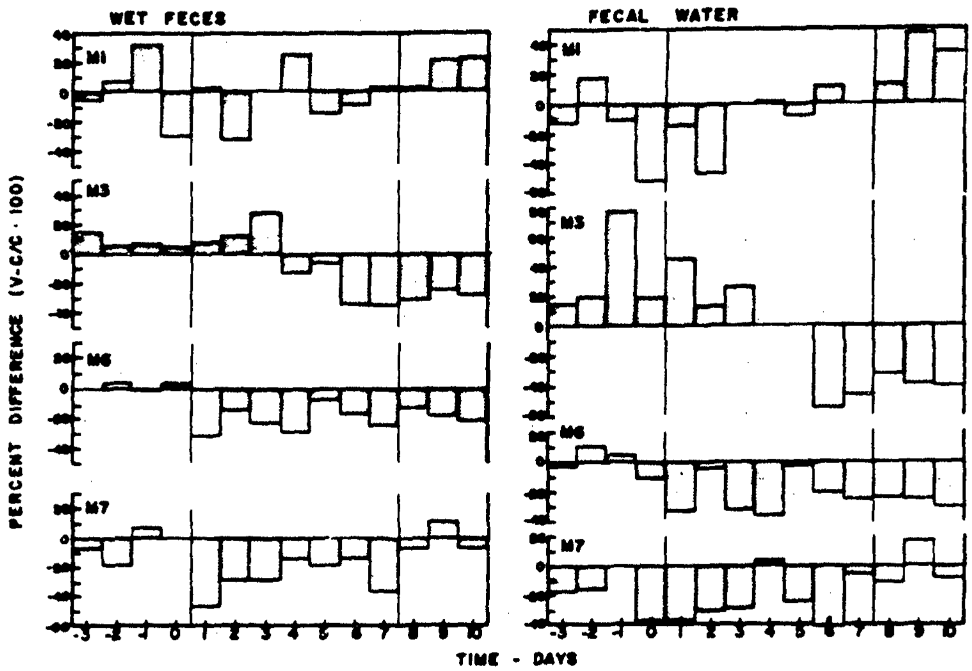

WET FECES
FECAL WATER
M1
M3
M6
M7
PERCENT DIFFERENCE (V-C/C · 100)
TIME - DAYS

Fig. I-A-2

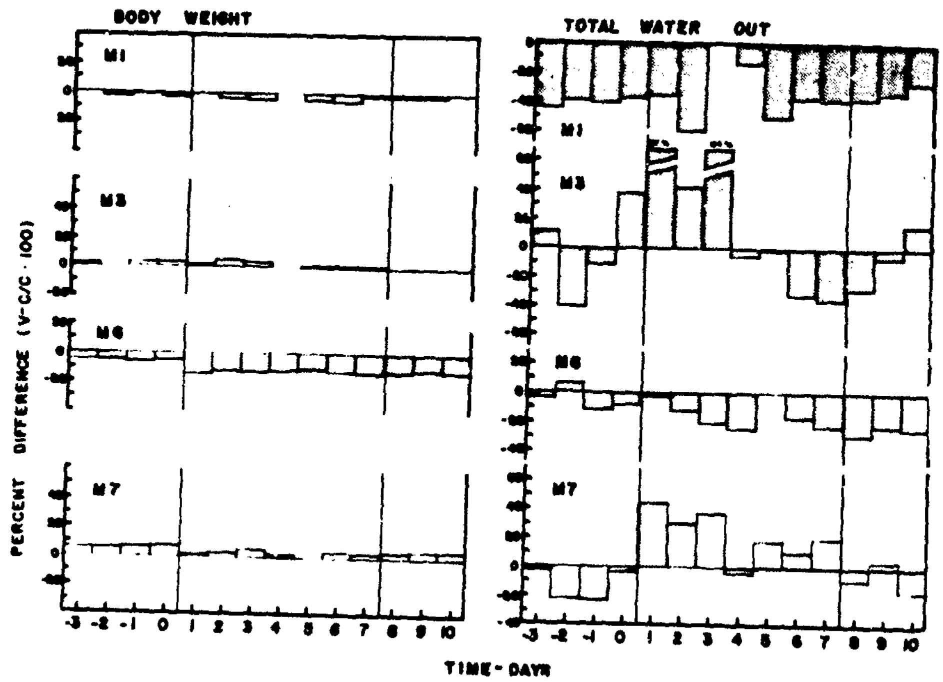

BODY WEIGHT
TOTAL WATER OUT
M1
M3
M6
M7
PERCENT DIFFERENCE (V-C/C · 100)
-3 -2 -1 0 1 2 3 4 5 6 7 8 9 10
TIME-DAYS

Fig. I-A-3

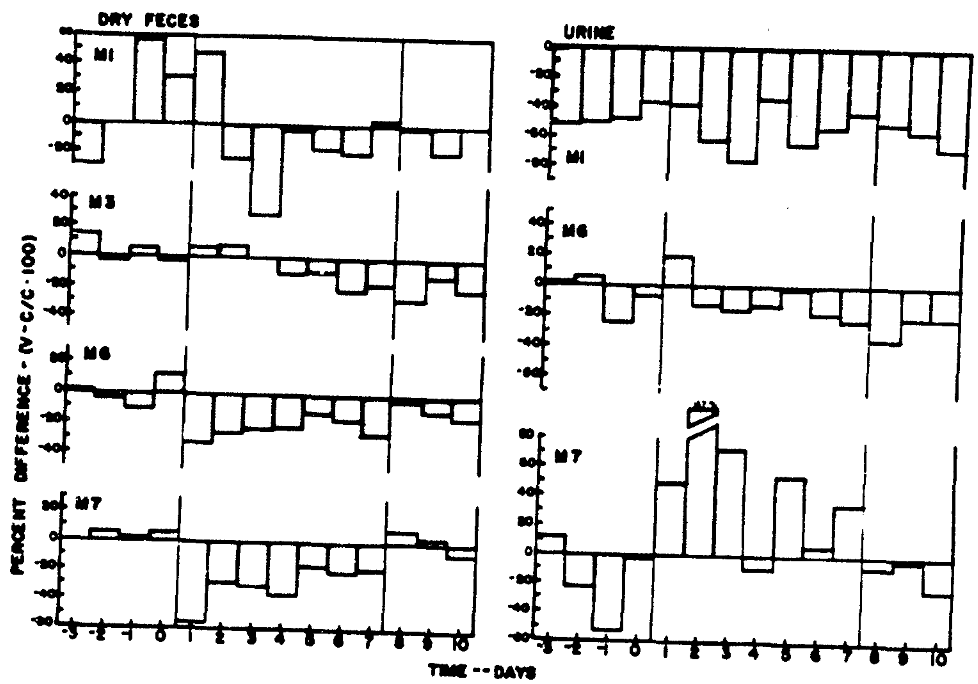

DRY FECES
URINE
M1
M3
M6
M7
PERCENT DIFFERENCE - (V-C/C·100)
TIME -- DAYS

Fig. I-A-4

RAT GROWTH CURVES

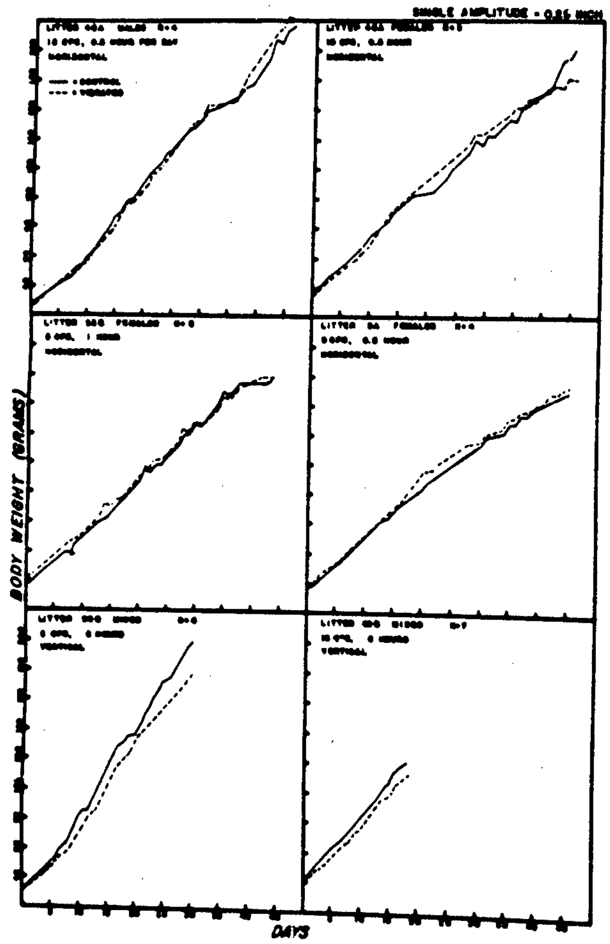


Fig. I-A-5

TABLE I-A-1. AVERAGE WEIGHT LOSS IN YOUNG RATS DURING VIBRATION PERIOD
(ALL EXPOSED TO VERTICAL VIBRATION)

Litter No.	Freq. CPS	Hours per day	Total hours of exposure	Mean weight loss GMS/day		Standard deviation		Significance P	N
				C	V	C	V		
31 A	5CPS	6	132	3.9	4.6	0.3	0.3	n.s.	66
32 A	5CPS	2	58	2.7	2.0	0.2	0.1	n.s.	145
50B	5CPS	6	102	5.2	4.8	0.3	0.2	n.s.	102
60B	10CPS	6	84	6.2	11.7	0.3	0.3	.01 level	112

B. EFFECTS OF VIBRATION ON PREGNANT RATS

As part of a preliminary survey in this area 36 pregnant female rats were exposed to vibration in the vertical plane. The frequency selected for this study was 20 CPS at 0.25-inch single amplitude. No mortality was observed at this level in normal female rats by Schaefer et al. (30). Earlier studies in this laboratory also indicated that this was not a lethal level of vibration for normal female rats.

Pregnancy was diagnosed by a great increase in daily weight. This technique has proven useful in our laboratory and delivery date can be estimated ± 2 days by this technique in normal rats.

Table I-B-1 lists the results of this study for individual animals. Table I-B-2 summarizes the data in terms of lethality by week of pregnancy, and by plane of vibration. Contrary to the normal animal, vertical vibration of this intensity is quite lethal in a very short period of time. About half of the rats in their third week of pregnancy died within half an hour on the shake-table. Another quarter of the animals succumbed within 12 hours of the exposure. The ability of vertical vibration to kill pregnant rats is dependent on the length of pregnancy. No rat exposed to vibration in the first week of pregnancy died. This possibly indicates that vibration death is a weight-related phenomenon. Earlier studies (Report No. 3) on dietary deficiencies and lethal vibration paradoxically indicated that a protein deficiency protected the animal when the mean dying time was compared to litter-mate controls. This paradox was resolved when equal-weight control animals were used as the basis of comparison.

Vibration death in pregnant rats differs from that in normal or nutritiously deficient rats, however. In the latter no evidence of trauma is observed with any consistency, whereas, in the pregnant rats autopsied after vibration death, massive hemorrhage of the uterus was apparent in every case. The amniotic fluid was dark red in color and major clots (1-4 mm in diameter) were noted clinging to the uterine wall. Since survivors were not autopsied, but allowed to go to delivery, it is not clear whether this condition existed in all pregnant rats vibrated. Hence, this factor alone may or may not be directly related to the cause of death. Interestingly enough, only one rat vibrated in her third week of pregnancy began a spontaneous abortion during the exposure.

Table I-B-3 summarizes the change in delivery date from that expected. Changes of one day only were not considered. Delays in delivery were from two-six days and early deliveries ranged from two-five days. The number of surviving animals being only 22, not too much significant information can be drawn from these data. It does indicate that a possible alteration of the normal gestation does occur when the pregnant rat is exposed to these levels of vibration.

TABLE I-B-1.

Rat No.	Date vibrated	Date due	Date delivered	No. born	No. weaned	Week of pregnancy
	20 CPS, 1/4", Horizontal, 1 hour.					
45	2-16	2-21	2-17	5	0	3
46	2-12	2-19	2-19	11	9	3
46	4-19	4-26	4-21	11	11	2
30	2-23	2-29	----	--	--	3
32	2-26	3-6	3-13	11	11	2
38	4-19	4-24	4-19	9	9	3
36	4-21	4-28	4-24	2	2	3
	20 CPS, 1/4", Vertical, 1/2 hour.					
52	7-29	7-31	*			3
64	7-29	8-4	8-6	2	2	3
A-9	7-29	8-1	*			3
A-2	10-17	10-31	10-27	6	6	1
A-8	10-17	10-27	----	--	--	2
B-87	10-18	11-1	10-29	8	8	2
A-10	10-18	10-21	*			3
A-28	10-24	10-30	11-3	6	6	3
A-29	10-25	10-30	*			3
A-11	10-26	10-30	11-1	3	0	3
B-51	10-27	10-30	*			3
B-71	11-7	11-21	----	--	--	1
B-38	11-7	11-21	11-22	3	3	1
A-81	11-8	11-23	11-20	5	5	1
A-33	11-8	11-28	11-26	5	5	1
A-80	11-18	11-28	*			2
B-90	11-18	11-25	11-27	11	10	2
A-11	11-28	12-4	----			3
A-55	11-28	12-5	12-4	3	0	3
B-68	11-29	12-7	*			2
B-6	12-6	12-11	*			3
A-1	12-6	12-12	----			3
C-2	12-6	12-11	*			3
A-0	11-30	12-2	*			3
B-28	1-26	2-1	*			2
B-77	1-26	2-1	----			2
A-100	2-21	2-25	*			3
A-110	2-21	2-25	*			3
A-81	2-21	2-26	*			3
A-11	2-21	2-26	*			3
B-1	2-21	2-25	*			3
A-2	2-22	2-26	*			3
B-2	2-24	2-24	*			3
B-36	2-24	2-26	*			3

* = died

TABLE I-B-2.

Pregnant Rats

Week of pregnancy	No. of animals	Died during	%	Died after	%	Survived	%	Survivors Producing
20 CPS, 1/4", Vertical, 1/2 hour.								
1	6	0	0	0	0	6	100	5
2	7	1	14.3	2	28.6	4	57.1	2
3	23	11	47.8	6	26.1	6	26.1	4
20 CPS, 1/4", Horizontal, 1 hour.								
2	2	0	0	0	0	2	100	2
3	5	0	0	0	0	5	100	4

TABLE I-B-3.

Delivery of Survivors
Change of more than 1 day from expected.

	Delay in delivery	Early delivery	No delivery	No change in delivery
No.	4	8	6	4
%	18.2	36.3	27.3	18.2

SECTION II. DOG STUDIES

A. GENERAL RESPONSES OF DOGS TO WHOLE BODY VIBRATION

1. Procedure

Systemic studies of the responses of dogs to whole-body vibration were carried out in a manner similar to that used on the rat studies. Unrestrained animals were exposed to horizontal and to vertical vibrations in the frequencies 3, 5, 10, 15, and 20 CPS at amplitudes of 1/16-inch and 1/4-inch. Three beagle hounds or small mongrel dogs, weighing from 8-15 kg., were tested at each frequency and each amplitude. A like number of animals served as controls and received identical studies in the same room at the same time as the vibrated animals. Each test animal was exposed to one set of vibration parameters for one hour, two hours, four hours, six hours, and one hour on consecutive days. Body weights and rectal temperatures were measured before and after each exposure. Rbc, wbc, hemoglobin and hematocrit were determined before and after each one-hour run. Blood sugar and blood lactic acid were determined before and after each one-hour run and also before and after each four-hour run.

2. Results

Figures II-A-1 and II-A-2 show the loss in body weight per kilogram per hour in excess of that lost by control animals at the various frequencies and the two amplitudes to which they were exposed. It is evident that horizontal vibration at 1/16-inch amplitude was not particularly stressful at any frequency, nor was this amplitude stressful in the vertical plane until 20 CPS was reached. In the horizontal plane at 1/4-inch amplitude weight loss in grams per hour per kilogram of body weight over and above that lost by control animals was readily measurable but never large. In the vertical plane, however, beyond 10 CPS the losses were considerable.

Figures II-A-3 and II-A-4 show the cumulative weight loss on successive exposures. Again the vertical plane is considerably more stressful than the horizontal. (While animals move around in the cage, most of the vibration in the horizontal plane is in the direction of the long axis of the body; a preferred position for dogs.)

In the region of 5 CPS the animals tend to go to sleep in either plane. Rats did the same thing but at 3 CPS. Oxygen up-take studies on the dogs comparable to those done on rats are being made but are not completed.

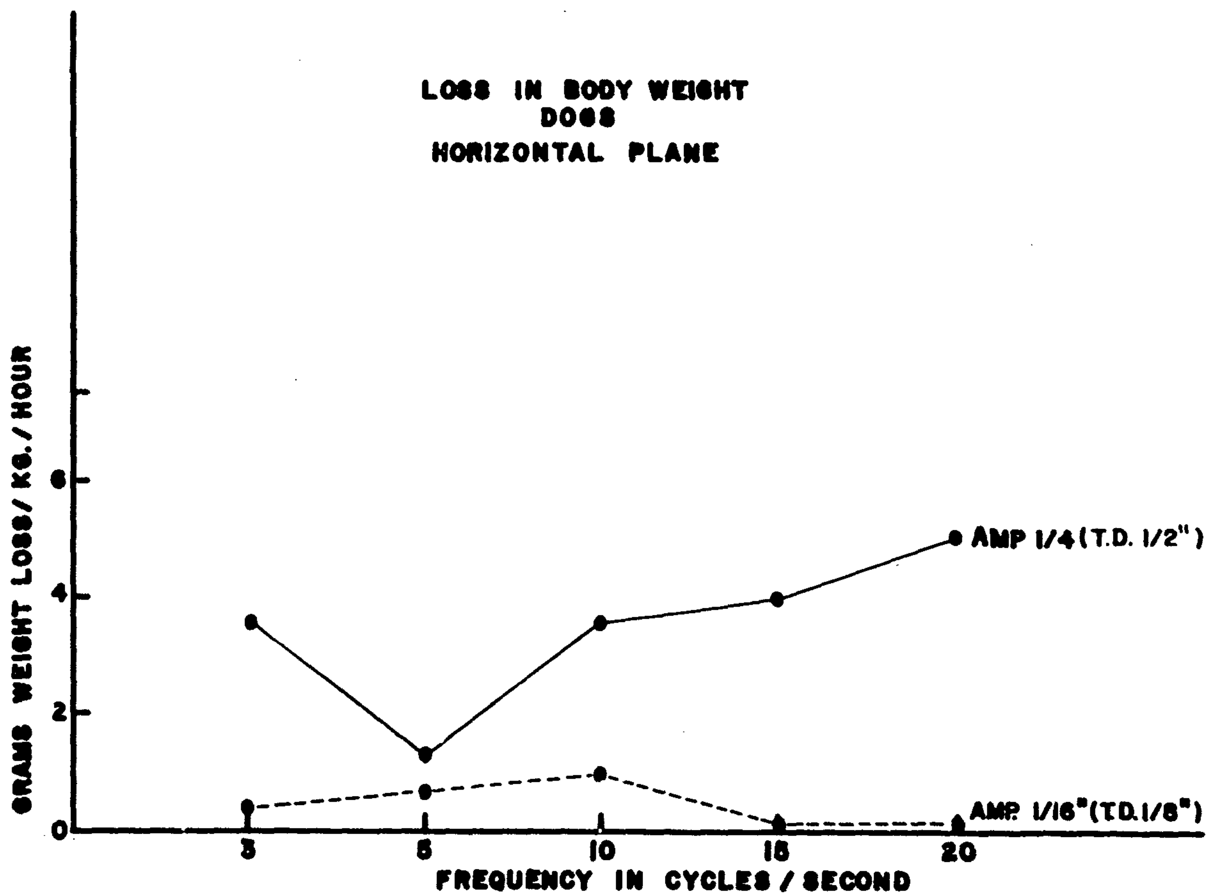

LOSS IN BODY WEIGHT
DOGS
HORIZONTAL PLANE
GRAMS WEIGHT LOSS/ KG./ HOUR
0
2
4
6
3
5
10
15
20
FREQUENCY IN CYCLES / SECOND
AMP 1/4 (T.D. 1/2")
AMP 1/16" (T.D. 1/8")

Fig. II-A-1

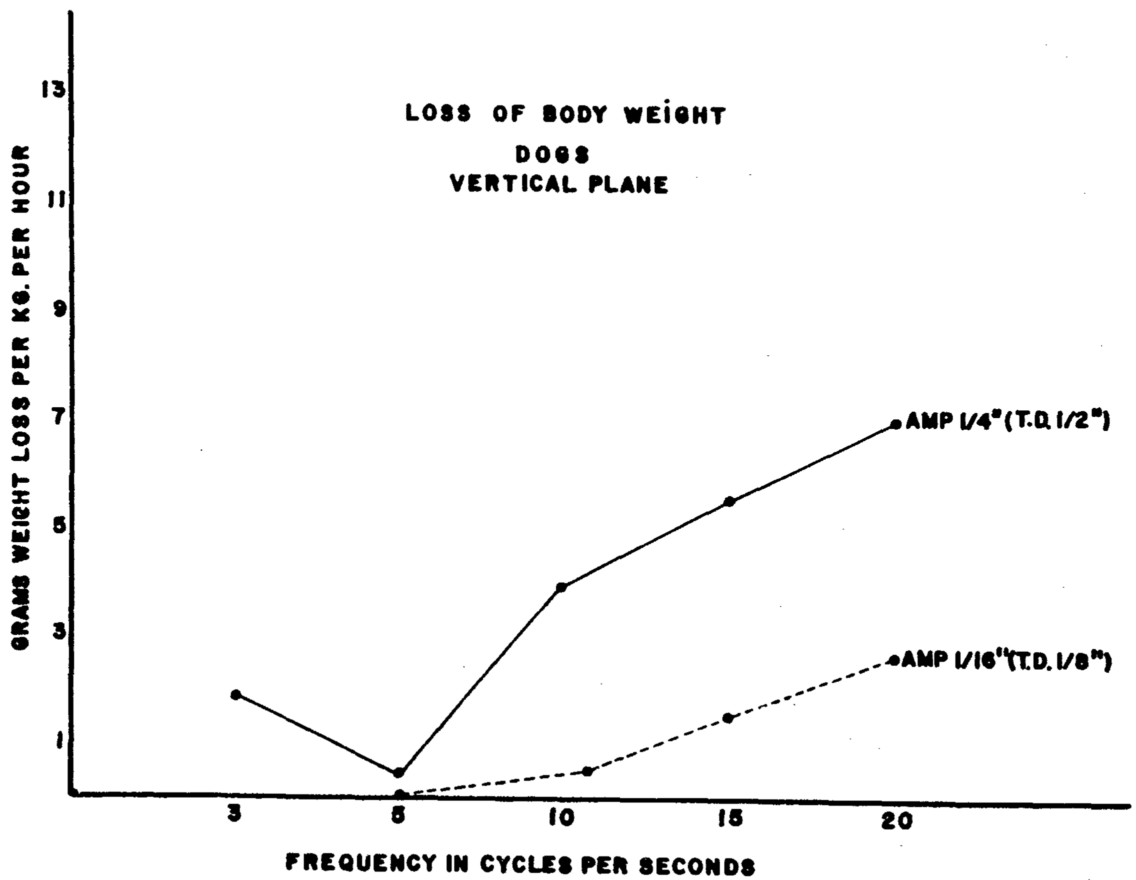
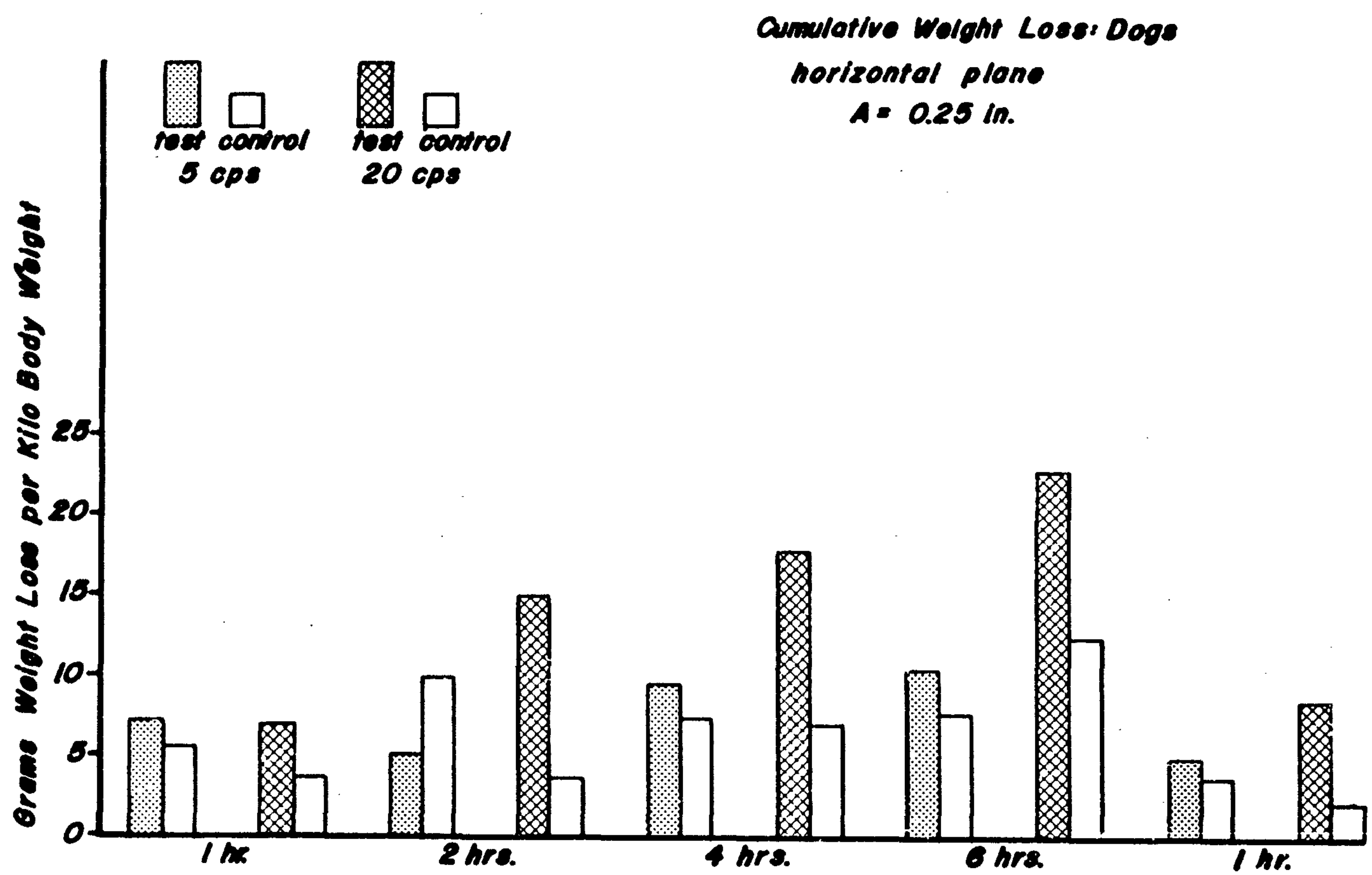

LOSS OF BODY WEIGHT
DOGS
VERTICAL PLANE
GRAMS WEIGHT LOSS PER KG. PER HOUR
13
11
9
7
5
3
1
3
5
10
15
20
FREQUENCY IN CYCLES PER SECONDS
AMP 1/4" (T.D. 1/2")
AMP 1/16" (T.D. 1/8")

Fig. II-A-2



Cumulative Weight Loss: Dogs
horizontal plane
A = 0.25 in.
test control
5 cps
test control
20 cps
Grams Weight Loss per Kilo Body Weight
0
5
10
15
20
25
1 hr.
2 hrs.
4 hrs.
6 hrs.
1 hr.

Fig. II-A-3

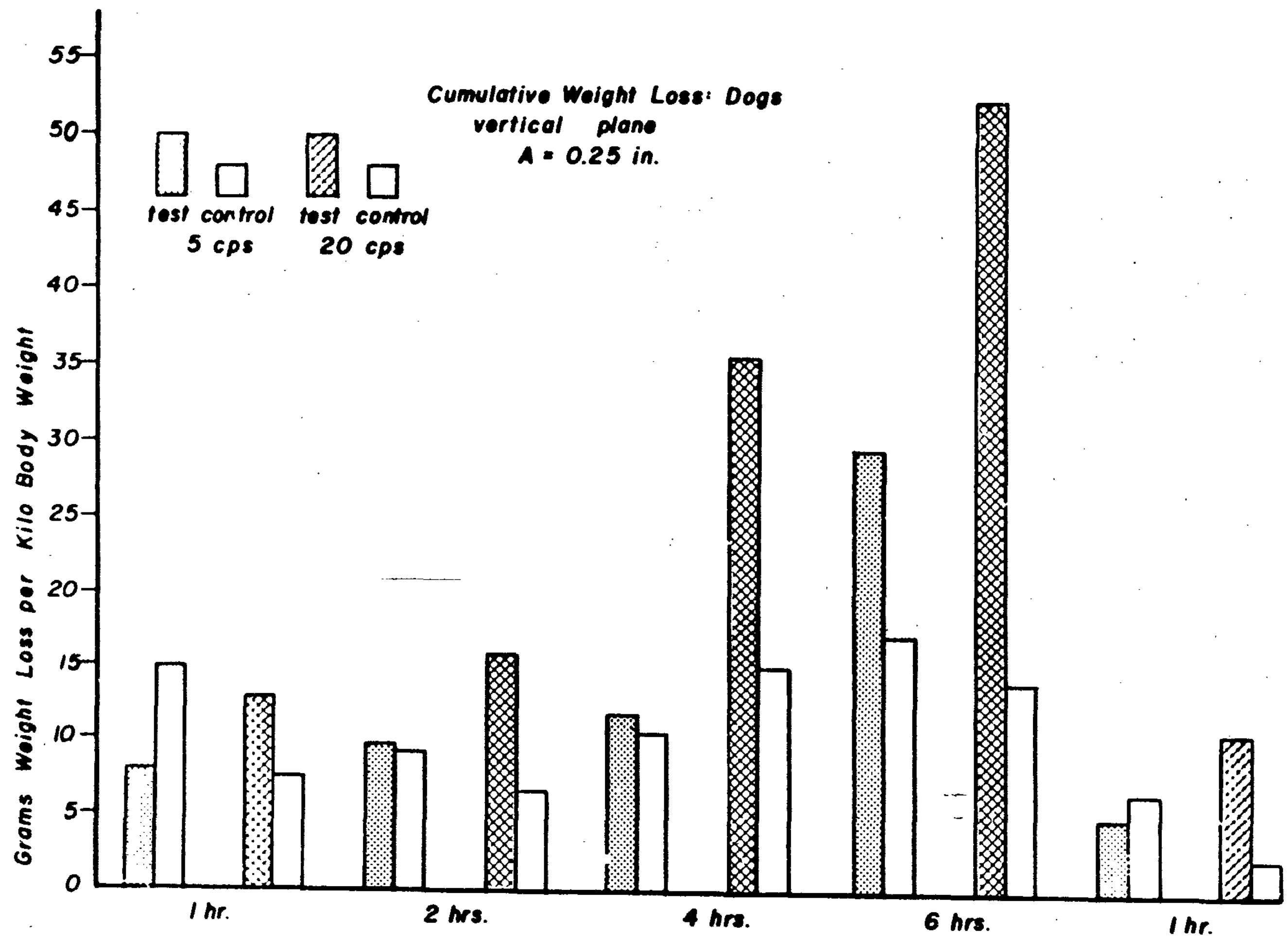

Cumulative Weight Loss: Dogs
vertical plane
A = 0.25 in.
test control
5 cps
test control
20 cps
Grams Weight Loss per Kilo Body Weight
55
50
45
40
35
30
25
20
15
10
5
0
1 hr.
2 hrs.
4 hrs.
6 hrs.
1 hr.

Fig. II-A-4

No consistent significant change in body temperature was noted on the test animals at any frequency in either amplitude in the two planes tested.

The rbc, hemoglobin, and hematocrit studies, which were made by a single highly competent technician, showed no significant changes. However, in either plane at all frequencies and both amplitudes, there is a consistent, very slight fall in all three measurements of the order of magnitude of 250,000 rbc per cu m.m., one-quarter gram of hemoglobin and 2% in hematocrit. Studies of the van den Berg for plasma hemoglobin indicate that this is not due to hemolysis. There is a slight tendency for the wbc to rise at any exposure above 5 CPS. The magnitude is not in excess of 10% of the resting rate and is believed to be a nonspecific response to stress.

The blood sugars and blood lactic acid levels did not change significantly at either amplitude at any frequency in the horizontal plane, nor in the vertical plane at 1/16-inch amplitude. In the vertical plane at 1/4-inch amplitude below 15 CPS no changes were noted. After four hours at 15 CPS blood sugars dropped 5-10 mgm% below the initial level and at 20 cycles in one hour blood sugars dropped 7-13 mgm%, and a 2.5 to 5.2 mgm% rise in blood lactic acid was noted in the test animals. All of the above changes were in excess of minor changes noted in the control animals and are statistically significant.

Comparisons of the two one-hour exposures to vibration of each animal a week apart fail to reveal any evidence of acclimatization to this form of stress in the stated period of time.

The most significant finding in these studies is that there is a definite species difference in response to vibration. Not only did we not kill dogs at any of these levels of vibration, but none was noticeably incapacitated even for brief periods after as much as six hours' exposure to 20 CPS at 1/4-inch amplitude in the vertical plane. (Some rats die at this level and all are seriously debilitated at the end of such a run.)

This difference is apparently due to the ability of the dog to absorb vibration so that little is transmitted through the entire body. Animal anatomical size may have something to do with this ability to absorb vibration when free to move about and protect himself by muscular activity.

B. BLOOD PRESSURE RESPONSES TO WHOLE-BODY VIBRATION IN ANESTHETIZED DOGS*

The effects of exposure to whole-body mechanical vibration on cardiovascular dynamics have been incompletely studied. Technical difficulties in obtaining reliable data have been the major factor deterring adequate investigation of this aspect of the physiological responses to vibration.

Franke (13) has reported a peripheral vasodilatation during exposure to local high-frequency (440 CPS) vibration. Schmitz and Boettcher (31) have reported an increase in systolic and a decrease in diastolic pressure in anesthetized dogs exposed to low-frequency (3-8) vibrations. Others (Loeckle (24), Loeb (23), Coermann (5), and Fowler (12)) have found indications of changes in blood pressure, but with no consistent pattern.

The variance of the data in the literature indicates the presence of a variable source of error in blood pressure measurement during vibration. It is possible that blood pressure during vibration becomes a time-dependent function, and, if this is true, all but direct continuous measurement would be highly variable. In direct measurement of blood pressure mechanical artifact from "catheter whip" may also be a large source of error. These studies were undertaken to determine the time relationship between blood pressure and vibration, and to evaluate the amount of mechanical artifact induced in the catheter by vibration.

1. Methods

To date eight mongrel dogs of moderate size (7 to 10 kg) have been subjected to the experimental conditions outlined below.

Animal Preparation: Each animal was anesthetized with sodium pentobarbital, (Nembutal), 30 mg./kg. body wt., administered intravenously. The animal was then secured to an animal board which was attached to a "shake-table." The trachea was exposed and intubated. The right femoral vein was exposed next and cannulated. The femoral vein cannula was then connected to a one-liter bottle of saline. Heparin, 0.2 unit/kg. body wt. was injected into the tubing connected to the venous cannula and flushed into the circulation with saline. Following heparinization, the artery to be catheterized was exposed; i.e., either the right carotid or left femoral or both. The distal end of the artery was tied, and the proximal end clamped. A small incision was made in the proximal segment, and the catheters passed toward the heart. After the desired amount of catheter had entered the artery, a ligature was placed around the artery and catheters proximal to the arterial incision. The animal was then ready to be vibrated.

*to be published in Archives of Environmental Health, October 1961.

Measuring System: Blood pressure was determined directly with intra-arterial catheters and Statham P23A pressure transducers. It was readily apparent, in preliminary studies, that several sources of error were present in the catheter transducer system.

Since the transducers themselves must be mounted some distance from the shake-table, an extraordinarily long catheter must be employed, which decreases frequency response. With a static transducer connected to a moving animal, it is possible that small, though significant, pressure changes are occurring in the catheter itself which would be algebraically added to the blood pressure.

To minimize this error source, the magnitude of this error was determined separately and subtracted from the blood pressure signal. To accomplish this, a dual catheter-transducer system was utilized (Hoover and Johanson, 17). Each catheter was filled with heparinized normal saline (0.9% NaCl with 0.1 unit heparin per cc.). Before entering the artery one of the catheters was sealed at the tip with heat and a fine silk ligature. This catheter-transducer system becomes the "error pickup." The other catheter, open at the tip is subjected to the same error sources, and also directly to the blood column. Using the driver amplifier of the oscillograph as a differential amplifier, the error signal is subtracted from the total signal of the open catheter leaving the blood pressure signal to be recorded. (See Fig. II-B-1.)

Vibration Exposure: All dogs were exposed to sinusoidal mechanical vibrations of 0-10 CPS at 0.25-inch amplitude (0.5-inch peak to peak) from 5 to 10 minutes at each frequency. The dogs were in the supine position, and the plane of vibration was horizontal and parallel to the long axis of the body. That is to say, the alternating force of vibration was directed in a plane parallel to the descending aorta of the experimental animal.

After the animal had been exposed to the selected frequencies, it was sacrificed with an overdose of nembutal (about 45 mg./kg. body weight). After the blood pressure had dropped to zero, the vibration exposure was repeated in order that "frequency response" data for the blood column might be obtained in the absence of control mechanisms and heart action.

2. Results

Figure II-B-2 shows typical recordings as obtained in these studies. It should be noted that the tracing labeled "motion artifact" shows no activity throughout the course of the experiment. It was found that, if the catheters were predominantly in line (i.e., parallel) with the direction of vibration, little or no artifact could be recorded. However, if they were placed perpendicular to the direction of vibration, appreciable artifact could be observed (Fig. II-B-3), and this amounted

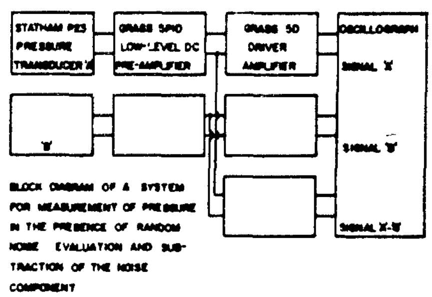
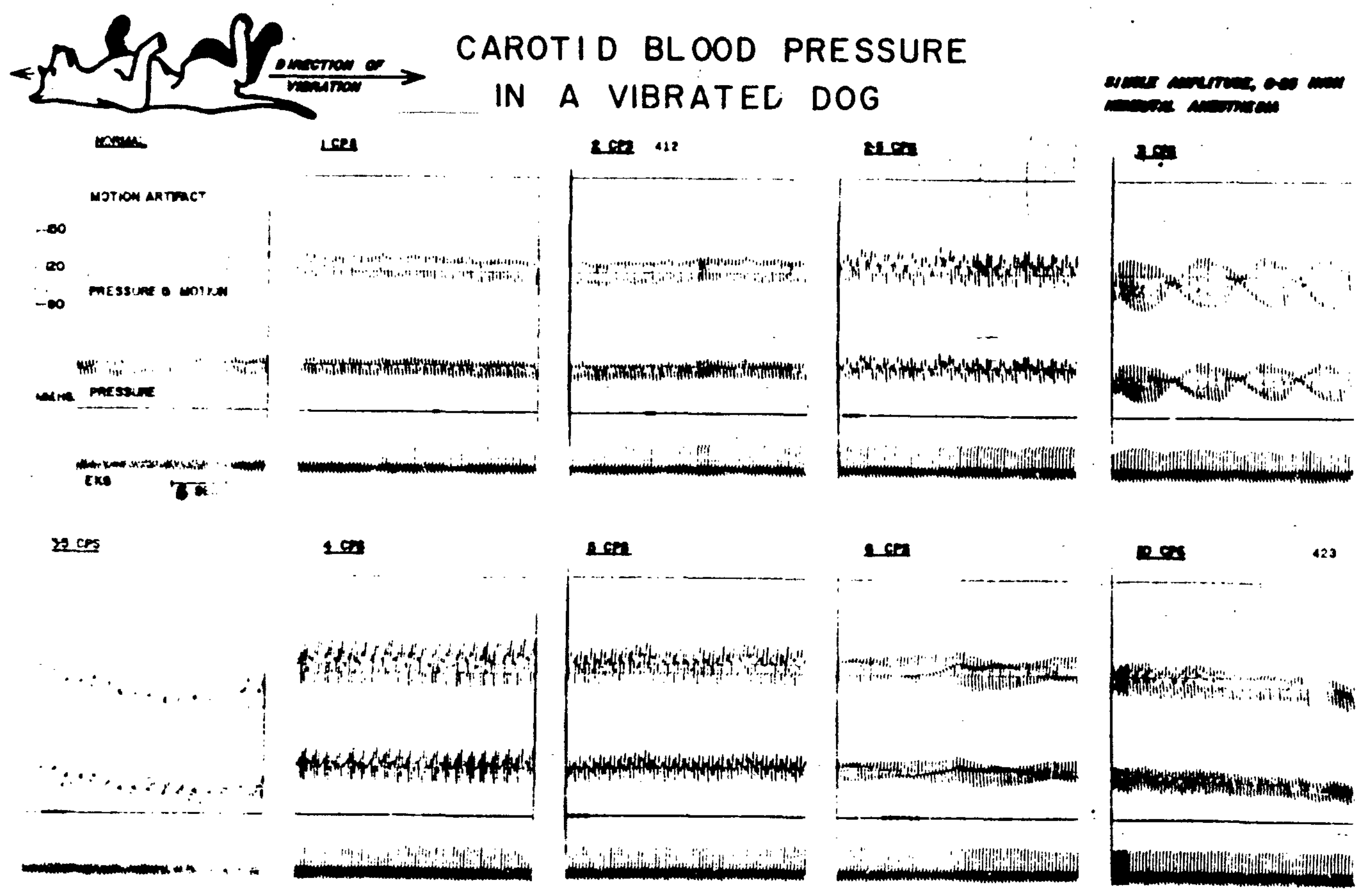

STATHAM P23 PRESSURE TRANSDUCER X
GRASS 5P1O LOW-LEVEL DC PRE-AMPLIFIER
GRASS 5D DRIVER AMPLIFIER
OSCILLOGRAPH
SIGNAL X
Y
SIGNAL Y
SIGNAL X-Y
BLOCK DIAGRAM OF A SYSTEM FOR MEASUREMENT OF PRESSURE IN THE PRESENCE OF RANDOM NOISE EVALUATION AND SUBTRACTION OF THE NOISE COMPONENT

Fig. II-B-1



CAROTID BLOOD PRESSURE
IN A VIBRATED DOG
DIRECTION OF VIBRATION
NORMAL
1 CPS
2 CPS
412
MOTION ARTIFACT
PRESSURE & MOTION
PRESSURE
MM HG
EKG
4 CPS
423

Fig. II-B-2

DOG BLOOD PRESSURE UNDER VIBRATION: 15 CPS, 0.25" SA

DOUBLE CATHETER-TRANSDUCER SYSTEM

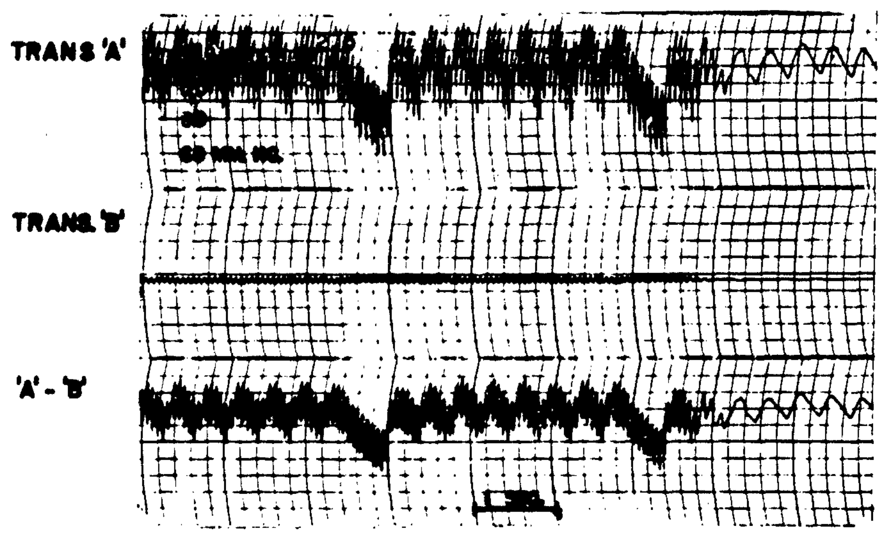


Fig. II-B-3

to about 5 mm. Hg. Observations of oscillograph patterns and photographic records (Visicorder) revealed that the limited frequency response of the pen writing system was not a factor in observing artifact, nor was it a factor in determining the complex patterns shown in Fig. II-B-2.

The patterns observed at various vibration frequencies seem to be the result of the addition of the forces of blood pressure and vibration. The phenomenon of beat frequencies has been studied in the acoustical sciences. Basically a beat frequency is the difference between the two added frequencies and is most predominant when these frequencies are close together. In Fig. II-B-2 the pulse frequency is 156 beats per minute or 2.6 per second. At vibration frequencies of two to five cycles per second (CPS) typical beat frequencies can be seen. In none of the experiments did the observed beat frequency approximate that expected on the basis of theory.

Indirect evidence to substantiate the beat frequency relationships in the vascular system was obtained by electrical analog techniques. Two sine wave generators were connected to the recording system so that each signal could be observed and the two signals could be added and recorded. One generator was set at a frequency comparable to the heart rates observed in the dogs, while the other was varied through the frequency range used in vibration exposure. The results were very similar to those shown in Fig. II-B-2. Quantitation of these relationships is in progress using an analog computer.

At a vibration frequency of 6 CPS, a secondary pattern may be noted. Above 6 CPS the frequency difference became great and the beat frequency phenomenon was no longer observed. In its place a pattern of the pulse pressure was observed with the vibration force altering a single pulse several times, without altering its systolic and diastolic levels.

Since a wide variation in pulse pressure was observed, and the rate of variation depends upon the frequency of vibration, this information alone is not adequate for a description of the blood pressure response to whole-body vibration. However, the integrated mean pressure will take these variations into account and weigh each pulse according to frequency and amplitude. Figures II-B-4 through II-B-7 show the systolic and diastolic pressure ranges with the integrated mean pressures for the carotid artery, femoral artery, thoracic aorta, and abdominal aorta, respectively. In the carotid artery, there is a tendency for the mean pressure to drop slightly as frequency increases to 5 CPS after which it begins to rise toward the resting level. In the femoral artery, sharp dips in the average pressure curve are noted 3 CPS and at 7 CPS. The pressure curves for the thoracic and abdominal aorta are similar. There is a sharp drop at 2.5 CPS and then a tendency to remain 15 to 20 mm. Hg. below the resting values. At 7 CPS they are

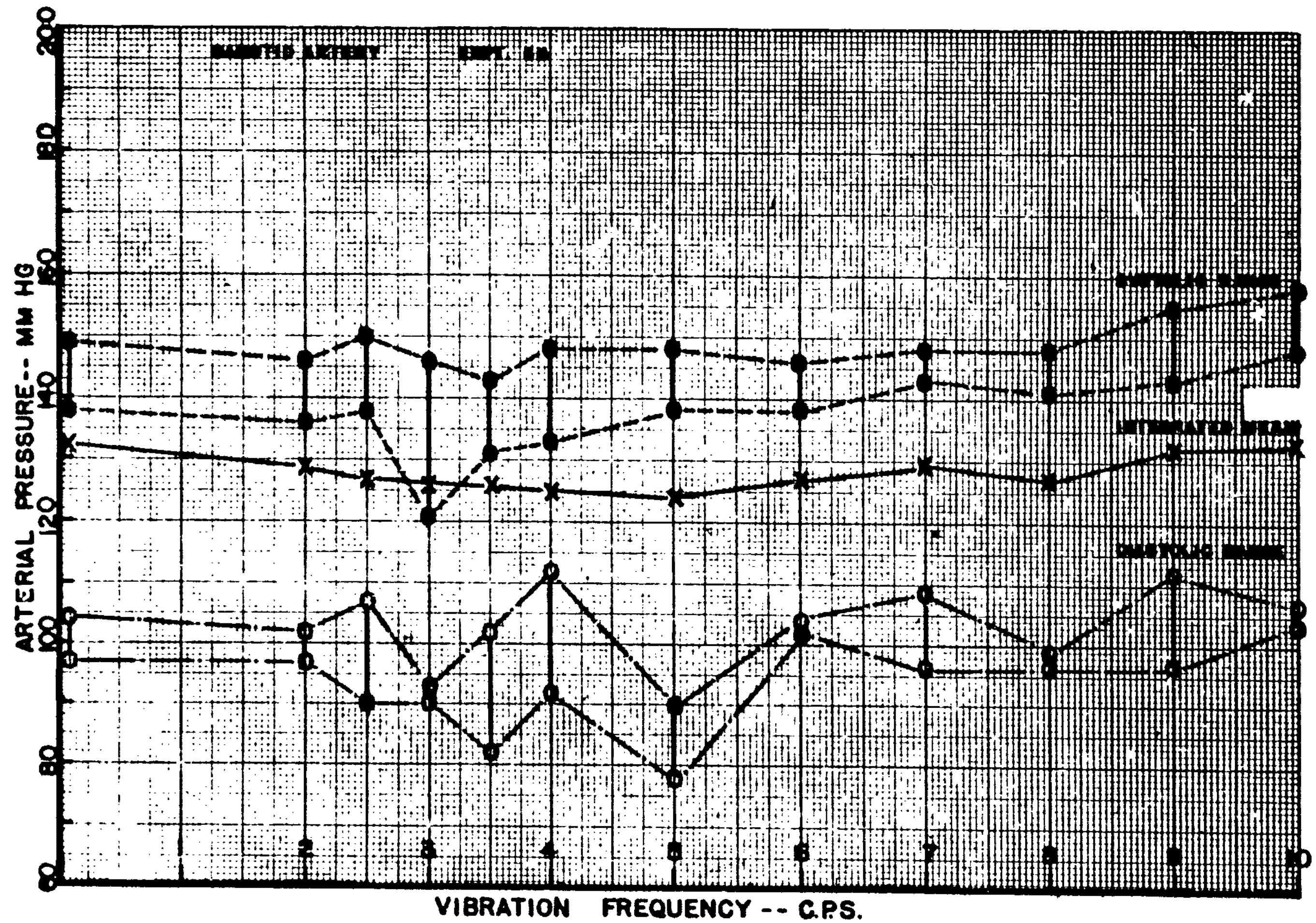

ARTERIAL PRESSURE-- MM HG
VIBRATION FREQUENCY -- C.P.S.
200
180
160
140
120
100
80
60
2
3
4
5
6
7
8
9
10

Fig. II-B-4

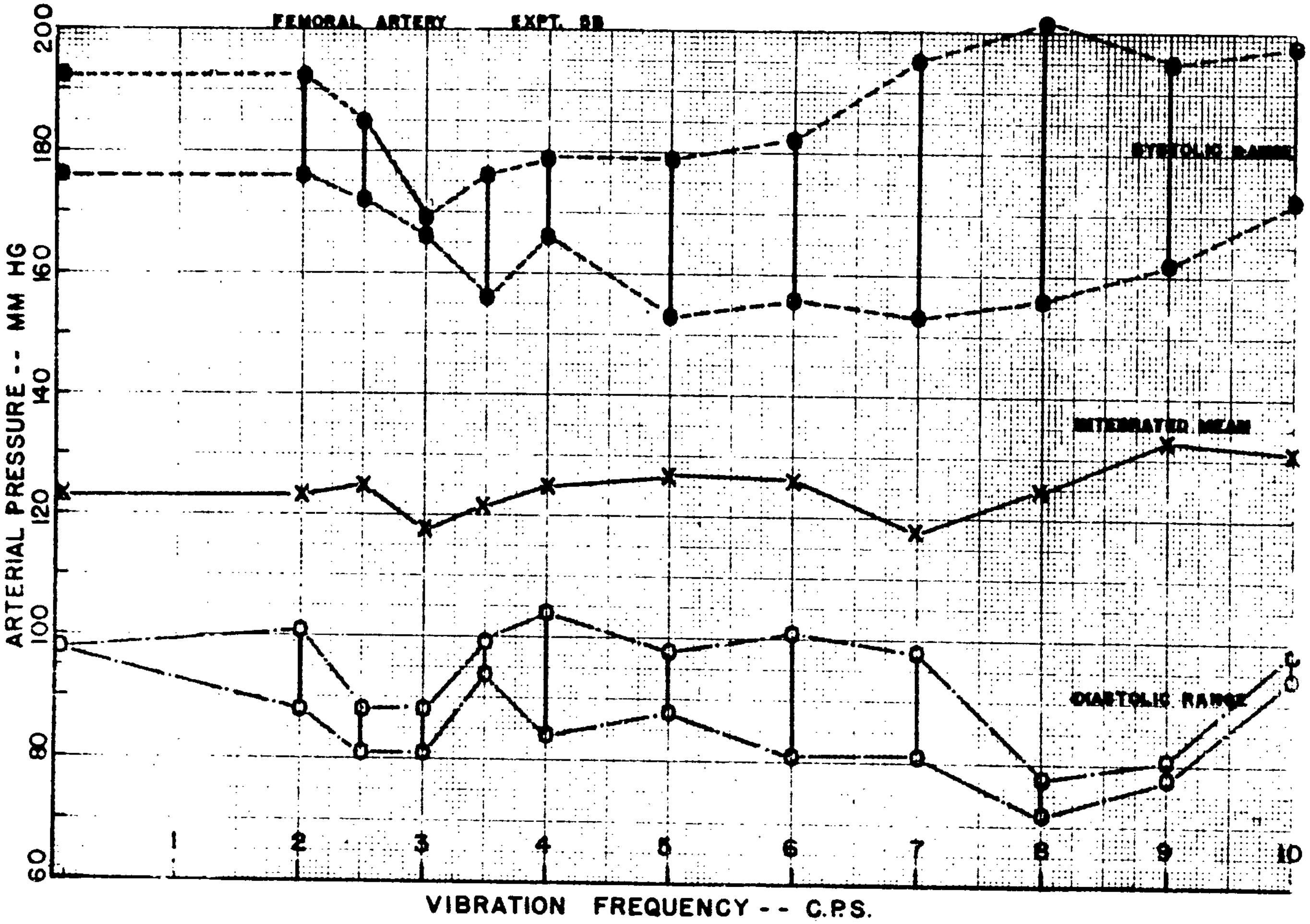

FEMORAL ARTERY EXPT. 8B
SYSTOLIC RANGE
INTEGRATED MEAN
DIASTOLIC RANGE
ARTERIAL PRESSURE -- MM HG
200
180
160
140
120
100
80
60
1
2
3
4
5
6
7
8
9
10
VIBRATION FREQUENCY -- C.P.S.

Fig. II-B-5

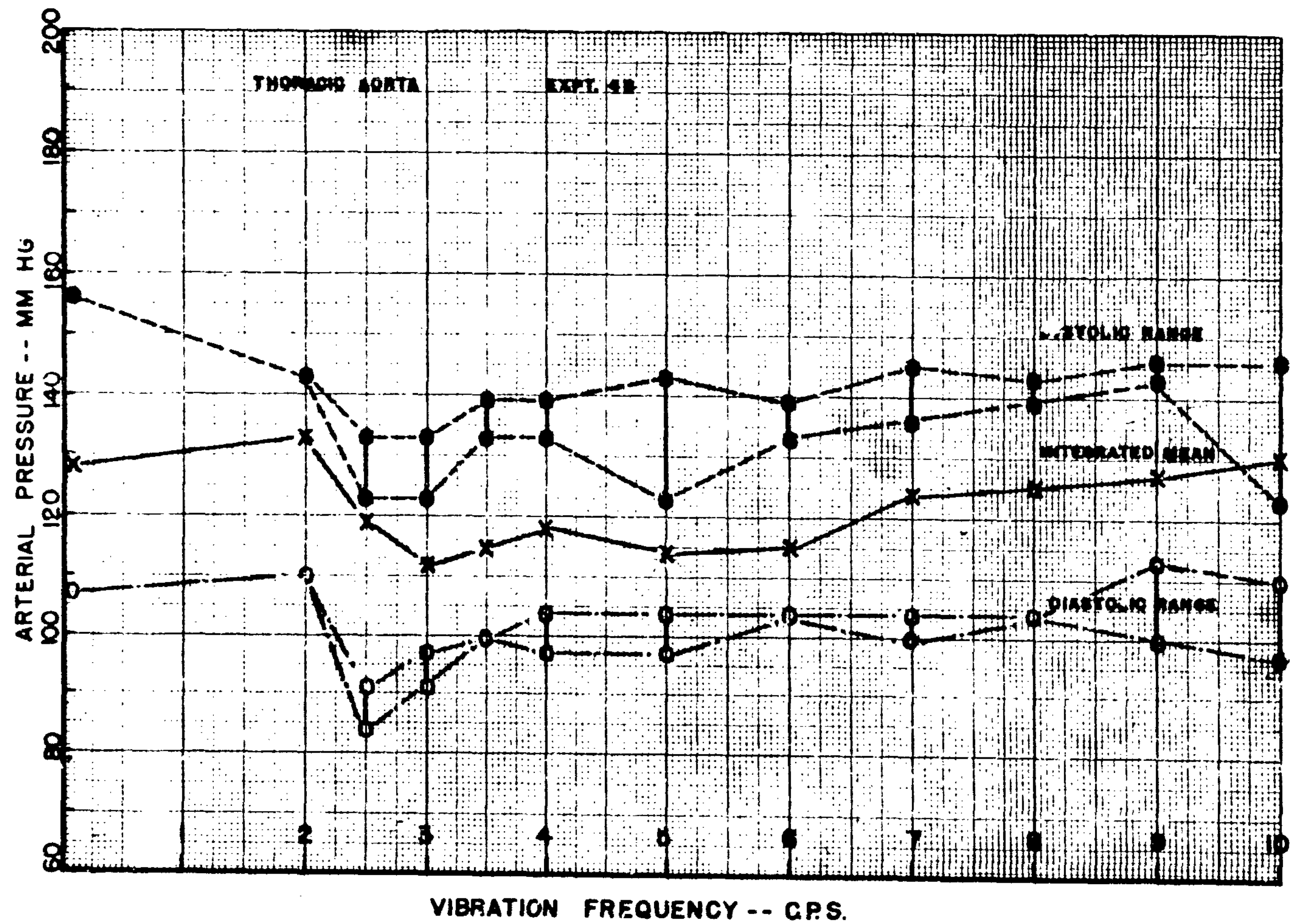

THORACIC AORTA
EXPT. 42
SYSTOLIC RANGE
INTEGRATED MEAN
DIASTOLIC RANGE
ARTERIAL PRESSURE -- MM HG
200
180
160
140
120
100
80
60
2
3
4
5
6
7
10
VIBRATION FREQUENCY -- C.P.S.

Fig. II-B-6

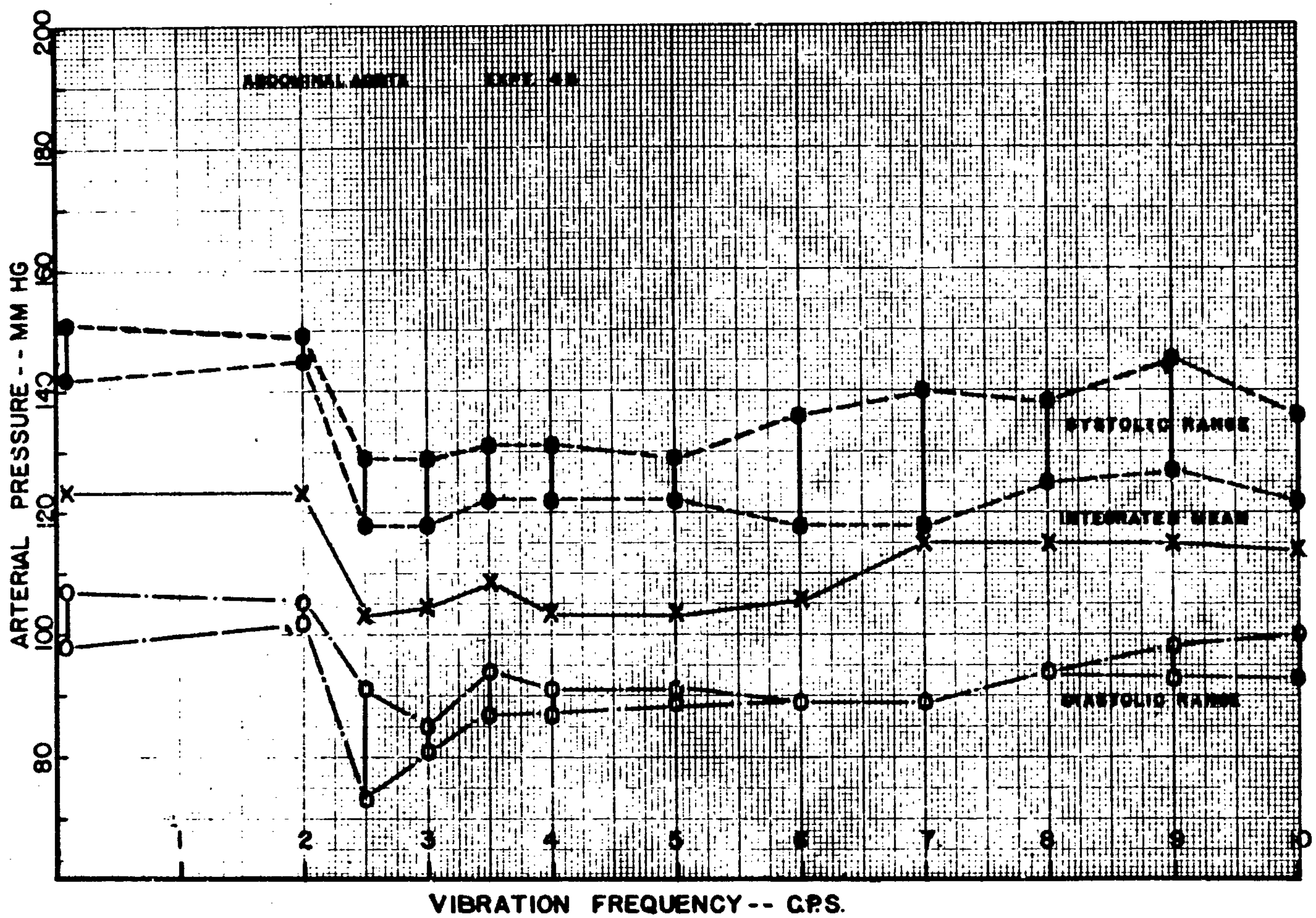

ABDOMINAL AORTA
SYSTOLIC RANGE
INTEGRATED MEAN
DIASTOLIC RANGE
ARTERIAL PRESSURE -- MM HG
200
180
160
140
120
100
80
1
2
3
4
5
6
7
8
9
10
VIBRATION FREQUENCY -- C.P.S.

Fig. II-B-7

elevated somewhat, but never quite reach the resting levels. It should be noted that the heart rate for the carotid-femoral study was 148 beats per minute throughout, while that for the aorta study ranged from 156-164 with a mean of 162 per minute. This translates to 2.46 and 2.70 beats per second, respectively.

The blood pressure response to vibration in the dead animal, or in a manner of speaking, "frequency response," for the arteries listed above is shown in Fig. II-B-8. The over-all picture varies widely for each artery studied, however, one point in common is clearly discernable. That is, all seem to have a peak frequency response at 2.5 CPS. Secondly, there seems to be a second peak response which varies for each artery except the aorta. These results have been consistent for all preparations.

3. Discussion

The data presented here are mainly descriptive in nature. It is believed that the technique used for measurement of arterial blood pressure in the vibrated animal represents an approach to studies of this nature. The reproducibility of the results indicates reliability or at least a consistent error.

The establishment of beat frequencies in the blood stream between pulse frequency and the vibration frequency is an interesting phenomenon. It is proposed that the beating of these frequencies is a result of adding to forces, the blood pressure and the vibration force, in a simple algebraic fashion. The validity of this theory would be easily established if the blood pressure pulse were a simple sinusoidal wave. However, the pressure pulse is a complex harmonic wave, and each harmonic will be effected by the vibration force.

From the data it may be inferred that some physiological changes are also occurring during vibration exposure. If a constant pulse pressure were altered solely by a sinusoidal vibration force, the integrated mean pressure should not be altered appreciably. This should be true since the integral of a sine wave is zero. However, decreases were observed in the integrated mean blood pressures, especially in the aorta. This would seem to be the result of some physiologic regulatory mechanism. Unfortunately these data do not permit elucidation of any possible mechanisms involved.

In many of the earlier studies, blood pressure was measured by the ausculatory technique, which yields blood pressure at a given instant in time. Because of the beat frequencies encountered, results using the ausculatory technique depend entirely upon what point in curve one happens to hit. This is probably the reason for the wide differences noted in earlier studies.

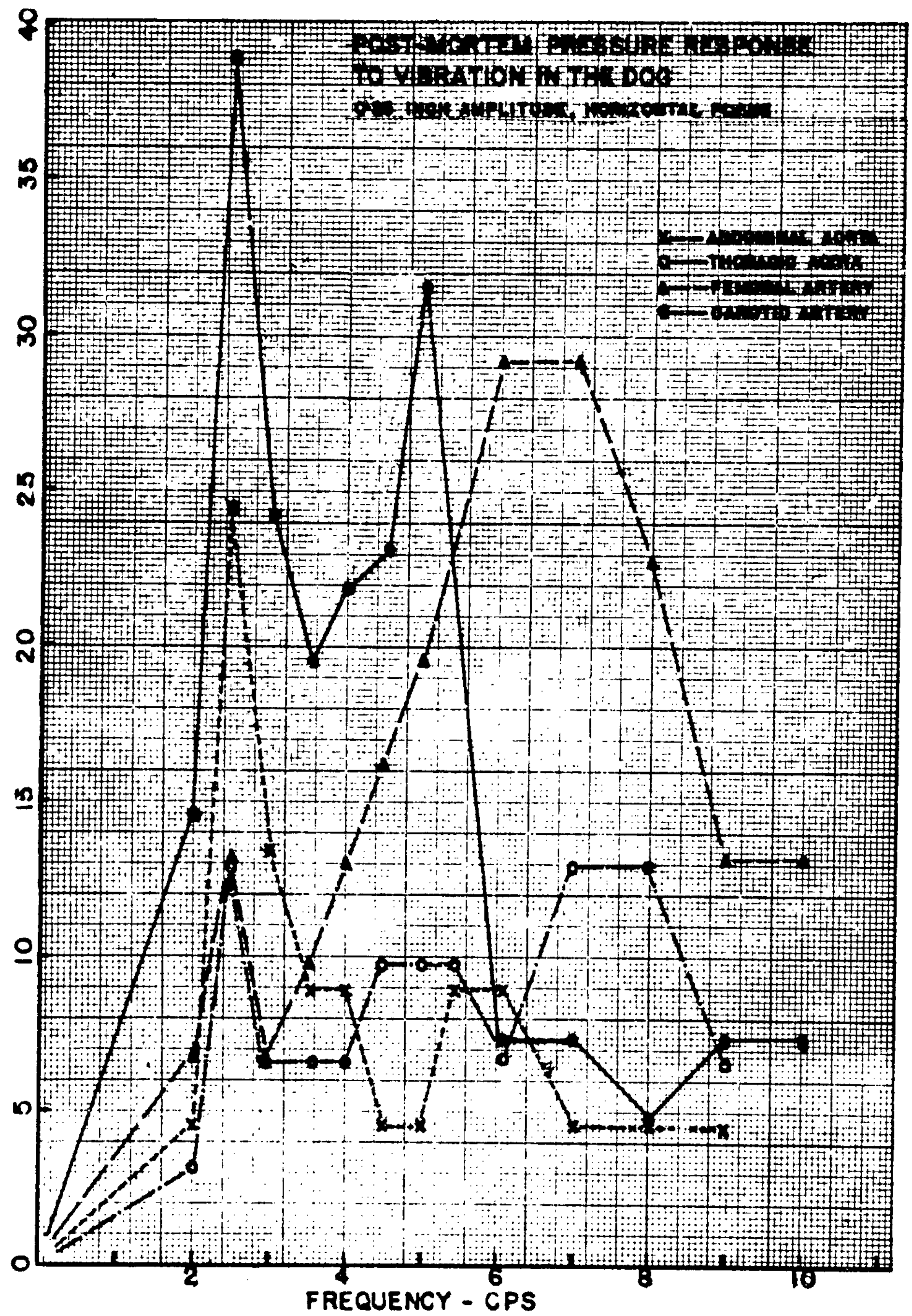

POST-MORTEM PRESSURE RESPONSE
TO VIBRATION IN THE DOG
0
5
10
15
20
25
30
35
40
2
4
6
8
10
FREQUENCY - CPS

Fig. II-B-8

The "frequency response" as seen in the blood pressure response of the dead dog supports the findings of Randall and Stacy (27), and Yanof and Stacy (37), especially as related to the femoral artery. These authors report a resonant point at about 3 CPS and Yanof found a second point between 5.6 and 7 CPS in the hindlimb of the dog using flow impedance measurements. In this study the femoral artery was found to have a resonant point at 2.5 CPS and another between 6 and 7 CPS.

4. Summary

A system for the direct measurement of blood pressure in dogs exposed to whole-body vibration is described. Vibration forces seem to be algebraically added to the blood pressure pulse in such a manner that beat frequencies are established. In addition, integration of the pulse pressure curves indicate that regulatory mechanisms bring about a small decrease in blood pressure during vibration exposure.

5. Acknowledgements

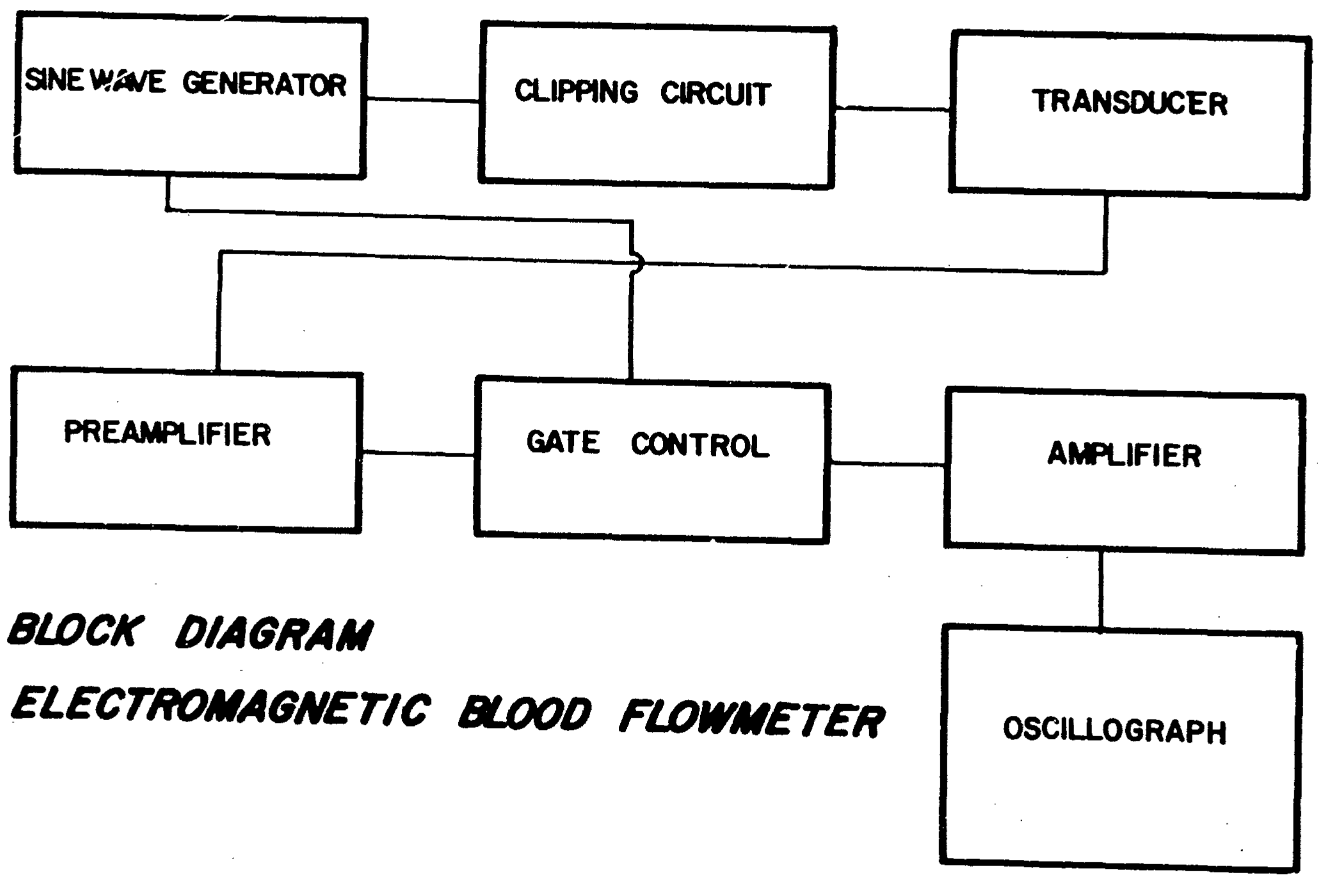
The authors wish to express their thanks to Dr. Ralph W. Stacy, Professor of Biophysics for his critical reading of this manuscript. Technical assistance of high quality was provided by Evelyn Johanson, Edward Whitehead, and Ruth Eells. Supported by NIH Grant No. RG5348.

C. BLOOD FLOW IN ARTERIES OF VIBRATED ANIMALS

In the last report of this project (Report No. 3) the development of an electromagnetic blood-flow meter was described. Since that time, a prototype circuit has been built and has gone through several modification stages. The largest modification was in the transducer excitation signal. Originally, a pulsed signal was intended, however, magnetic materials currently available, even high-grade computer memory cores, did not have adequate characteristics (particularly in terms of the B-H hysteresis curve) to permit operation on this basis, although it is still a theoretically possible system. Yanof had described a trapezoidal wave excited flow-meter circuit, with many apparent advantages. This circuit was rather complex in that the production of a trapezoidal wave requires several operations. It seemed to us that a clipped-sine wave would provide the same advantages without the complex circuitry. Figure II-C-1 shows the block diagram of the circuit as it now stands.

Three transducers have been built and tested. The first was a "flow through" model in which the flow was directed past the electrodes by a polyethylene tube. This model was used for calibration and sensitivity studies on normal saline (0.9% NaCl). Figure II-C-2 shows such a calibration curve. The current supplied the magnet was 0.9 amp, or twice the minumum current available from the circuit. Note that this current gives the flowmeter a large sensitivity (up to 1055 ml/min) and has relatively good sensitivity at 75 ml/min. There is a slight hysteresis in the calibration curve, and some non-linearity. At low flows this amounts to about 2% error, in the middle range the error is less than 1%, and in the high range, the error is quite large. Error in this from laminar to turbulent region is probably due to the change in flow at the higher flow rates.

The second transducer model was designed for use in acute animal preparations. It served as the prototype for the third model which was identical except for the provision of chronic implantation with electrical connections being made with a plug sutured to the skin of the animal. With the second model the recordings shown in Figs. II-C-3, 4, 5, and 6, were obtained. In this particular series, electrode contact was not ideal and serious artifact was evident when the animal was vibrated at frequencies greater than three cycles per second. However, the contact was adequate during the critical range of 2, 2.5, and 3 CPS. The vibration amplitude was 0.25 inch (displacement of .5 inch, 0.23G). The recordings show blood pressure on each side of the transducer and the differential pressure. Flow magnitude is closely related to the magnitude of differential pressure but with differing wave forms. Beating of frequencies between blood pressure and vibration forces occurred at 2.5 and 3 CPS, as was expected. The blood flow reflected this beating as evidenced by the cyclical variations in flow corresponding to the beat frequency. Although absolute flow values are not known for these



BLOCK DIAGRAM

ELECTROMAGNETIC BLOOD FLOWMETER

Fig. II-C-1

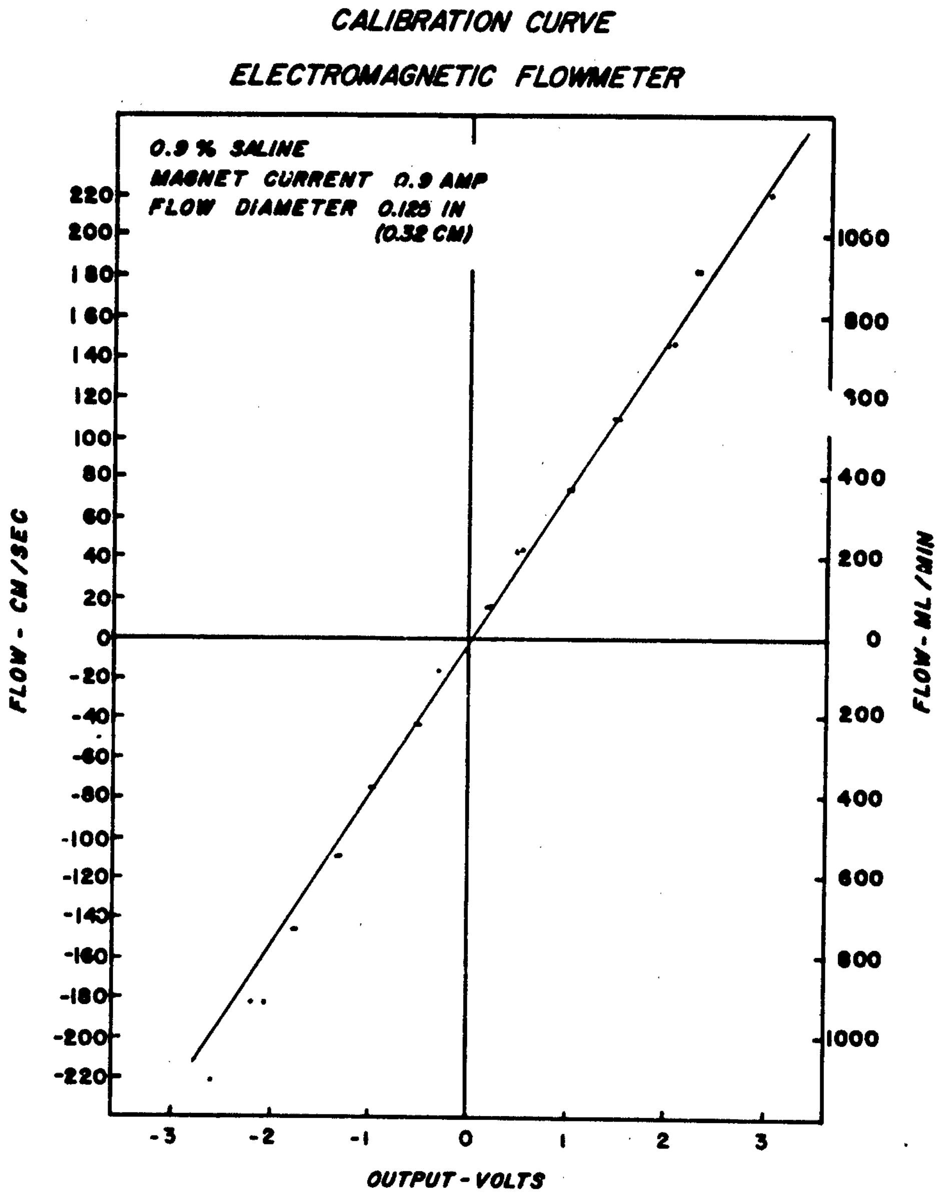

CALIBRATION CURVE
ELECTROMAGNETIC FLOWMETER
0.9 % SALINE
MAGNET CURRENT 0.9 AMP
FLOW DIAMETER 0.125 IN
(0.32 CM)
FLOW - CM/SEC
FLOW - ML/MIN
OUTPUT - VOLTS
220
200
180
160
140
120
100
80
60
40
20
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
-200
-220
1000
800
600
400
200
0
200
400
600
800
1000
-3
-2
-1
0
1
2
3

Fig. II-C-2

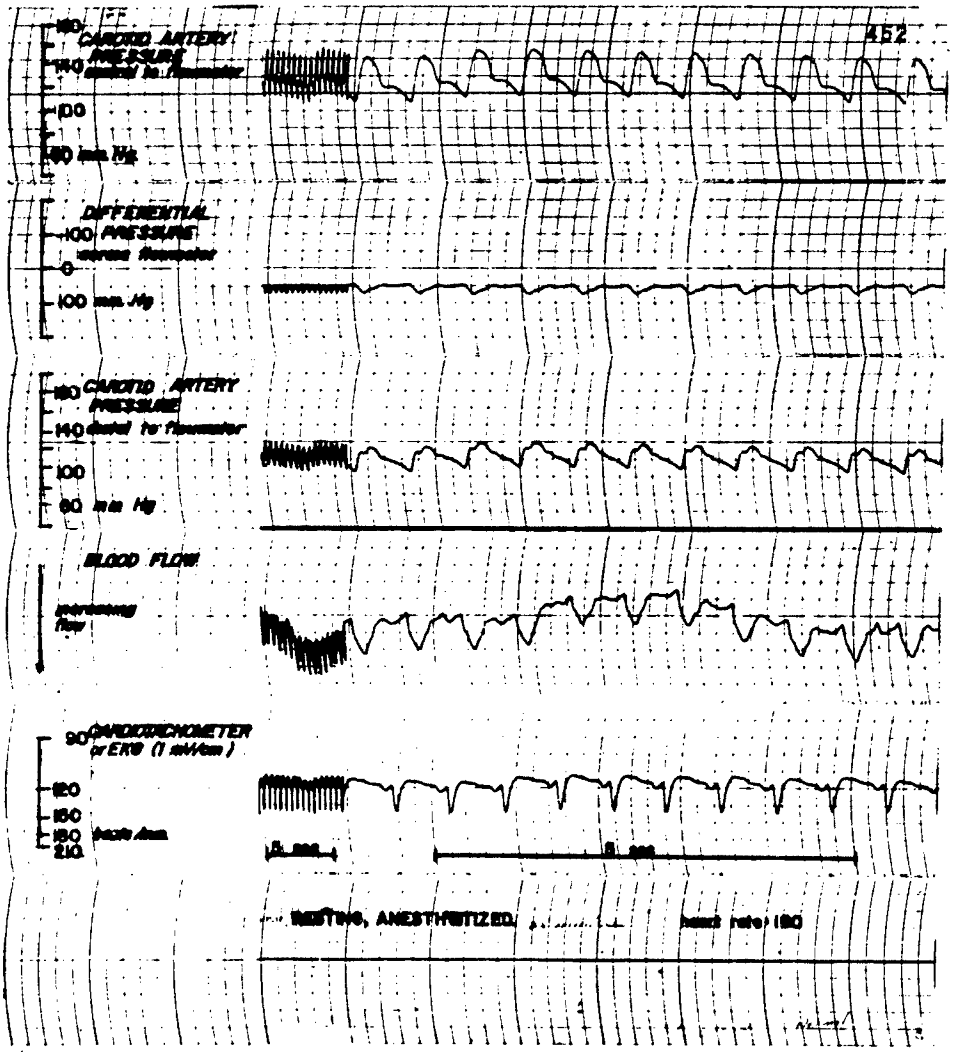

452
CAROTID ARTERY PRESSURE
DIFFERENTIAL PRESSURE
CAROTID ARTERY PRESSURE
BLOOD FLOW
CARDIOTACHOMETER
RESTING, ANESTHETIZED

Fig. II-C-3

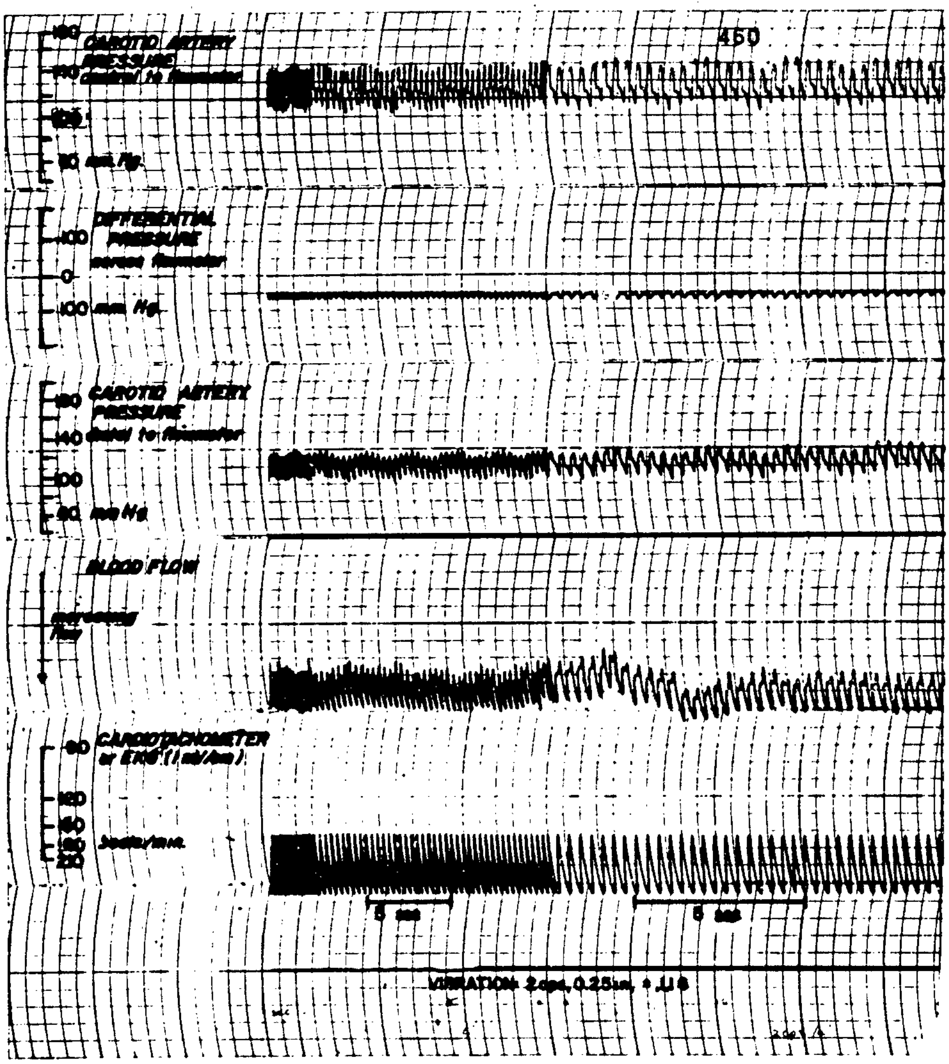

450
CAROTID ARTERY PRESSURE
DIFFERENTIAL PRESSURE
CAROTID ARTERY PRESSURE
BLOOD FLOW
CARDIOTACHOMETER
5 sec
5 sec
VIBRATION: 2cps, 0.25in., ±.11 G

Fig. II-C-4

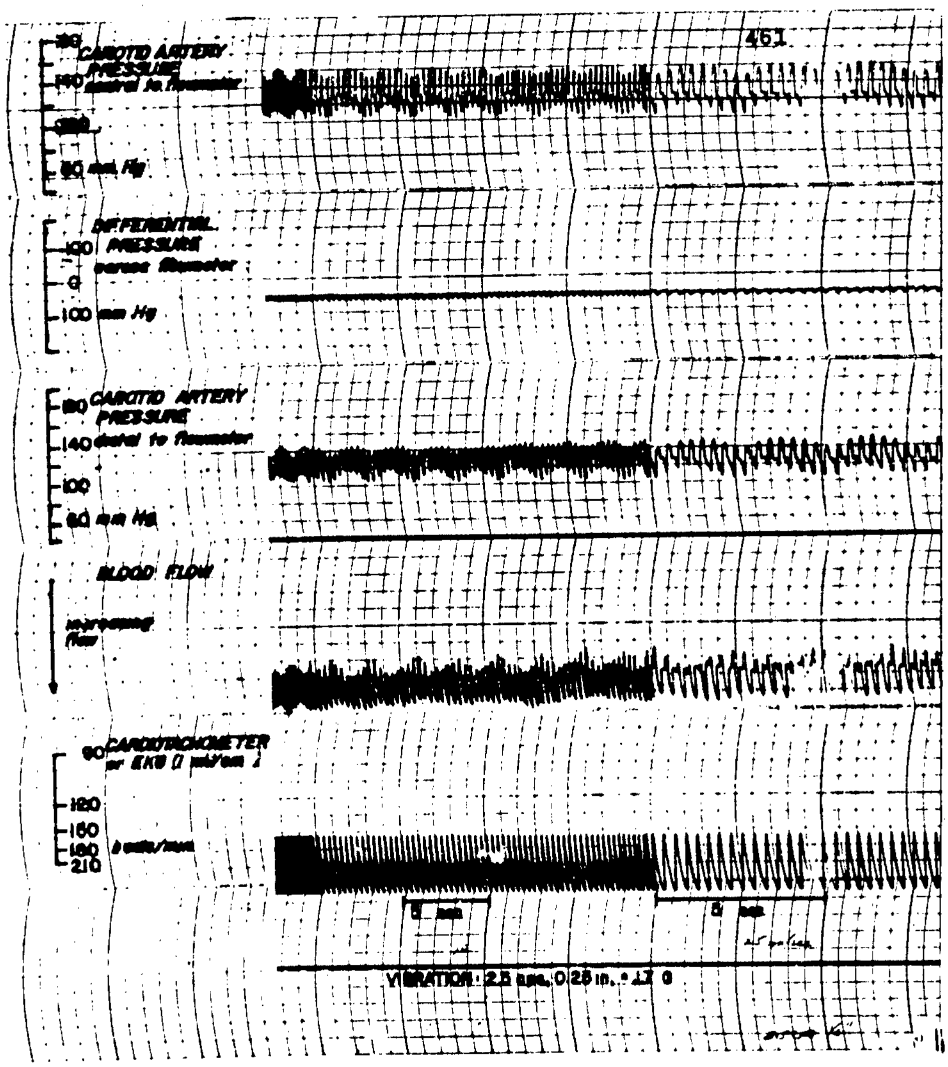

461
CAROTID ARTERY PRESSURE
central to flowmeter
mm Hg
DIFFERENTIAL PRESSURE
100
0
100 mm Hg
CAROTID ARTERY PRESSURE
distal to flowmeter
180
140
100
60 mm Hg
BLOOD FLOW
increasing flow
CARDIOTACHOMETER
90
120
150
180
210
beats/min
VIBRATION: 25 cps, 0.25 in., ±1.7 G

Fig. II-C-5

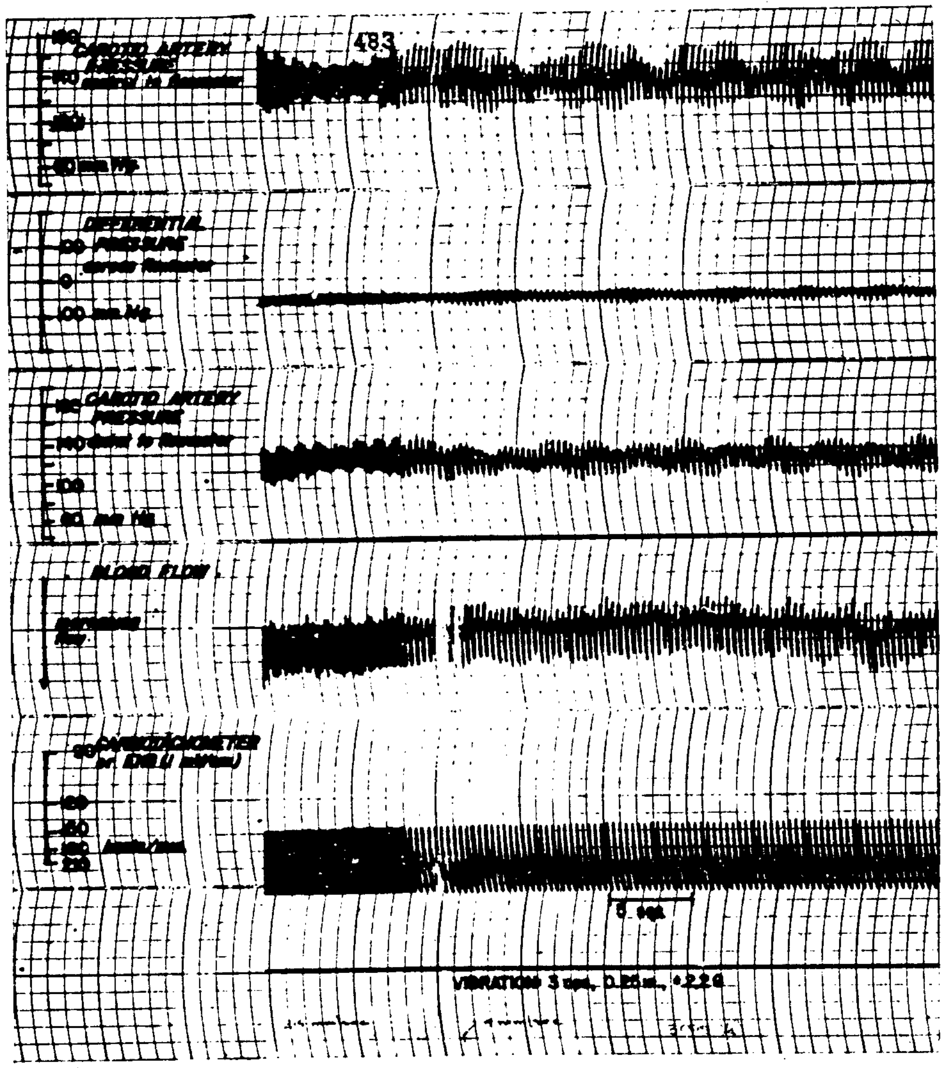

483
CAROTID ARTERY
PRESSURE
DIFFERENTIAL
PRESSURE
CAROTID ARTERY
PRESSURE
BLOOD FLOW
CARDIOTACHOMETER
5 sec.

Fig. II-C-6

tracings, flow magnitude was increased (greater flow being downward on these records) at 2 and 2.5 CPS and near normal at 3 CPS. The latter frequency produced greater pulsatile flow, however. This study served at the preliminary attempt for a series of similar studies to be performed in the coming year.

The third flowmeter transducer has been used in a study of the feasibility of chronic implantation. Figure II-C-7 is a photograph of this probe. The transducer itself is about 1.25 inches in diameter with the opening for the artery being about 0.25 by 0.375 inch. This probe was implanted on the iliac artery of a dog weighing about 14 Kg on July 11, 1961. The probe remained in the dog until August 31, 1961 at which time it was removed. At no time did the animal appear to be cognizant of the presence of the flow-meter or was there apparent evidence of severe occlusion of the iliac artery. The femoral pulse on the side of the implant (left) was always as strong as the pulse on the normal side. The major problem occurred at the site of the connector. The connector was sutured to the abdominal muscle mass, and to the skin. However, the skin around this area did not heal quickly and exudates were continually present. The exudates quickly infiltrated the connector assembly making electrical contact all but impossible. On about the fourth post-operative week, the edges of the wound began healing, but at the same time began an encroachment of the connector assembly. Attempts to measure flow in the fifth post-operative week required an "episiotomy" of the opening to obtain access to the connector. Exudates again prevented electrical connection, their source being mainly subcutaneous. A fourth flowmeter transducer is now being built which will allow the connector to extend beyond the skin level about two inches. This creates a problem in having the animal attack the connector, but will eliminate the problem of poor contact.

This approach to the measurement of blood flow in the un-anesthetized animal exposed to severe environmental conditions such as vibration seems promising. Further work on the technical details should eliminate the problems encountered to date.

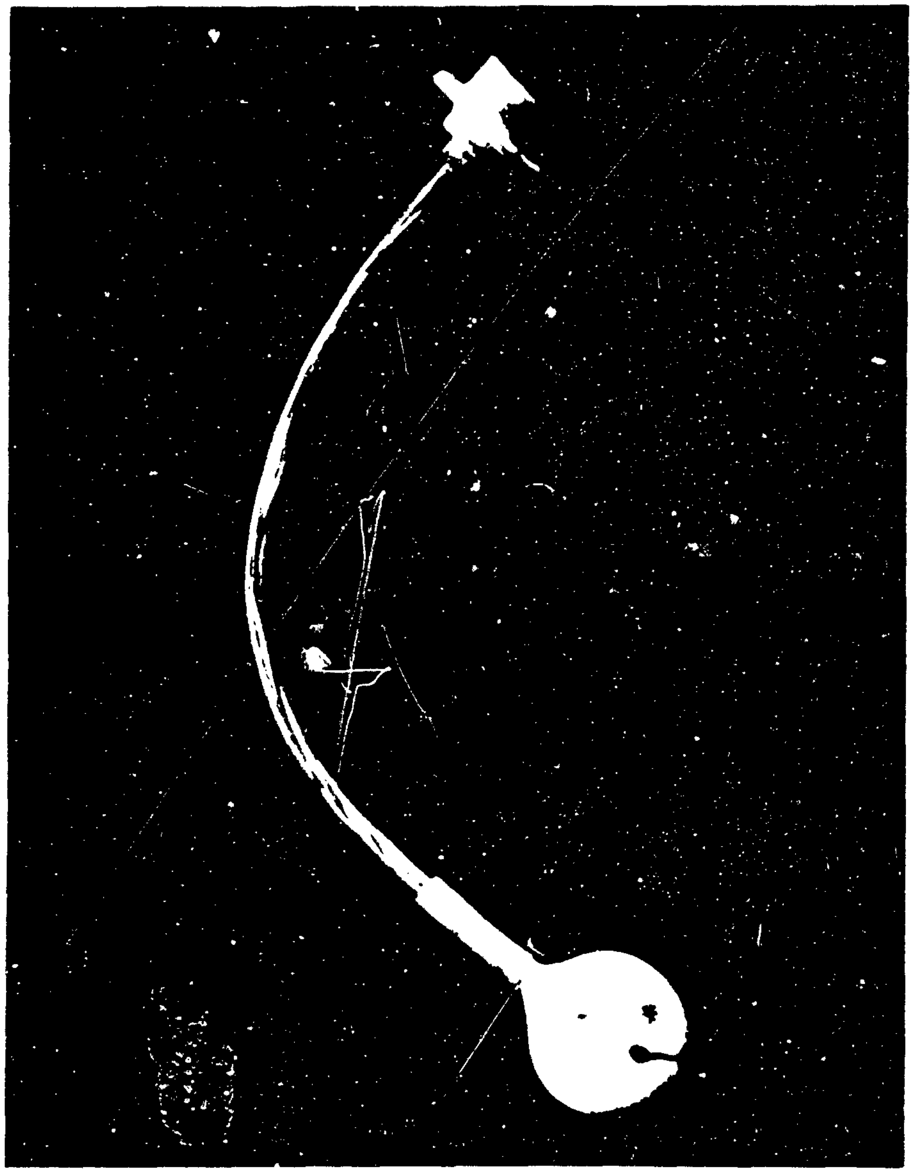


Fig. II-C-7. Electromagnetic Blood Flowmeter Probe

SECTION III. HUMAN STUDIES

A. HUMAN PSYCHOMOTOR PERFORMANCE DURING PROLONGED VERTICAL VIBRATION*

One useful approach to the problem of studying the effects upon human beings of such a fluctuating, dynamic, environmental stress as mechanical vibration, has been shown to be via the measurement of human ability to perform a standard task under varying conditions of vibration stress (14, 32). An earlier study in this laboratory indicated that human performance is significantly affected by differences in either frequency, amplitude, or plane of vibration (14).

The purpose of the study, which is the subject of this paper, was to shed further light on the role played by changes in amplitude and frequency on the ability of unrestrained human subjects to perform a tracking task under vertical vibration.

1. Methods and Equipment

In this study, simple sinusoidal mechanical vibration was used. The term amplitude refers to the vertical distance traveled from the resting position to the peak of a sinusoidal wave. Thus, amplitude is equal to one-half the total vertical displacement of the system. Frequency is the number of complete cycles per second. Six discrete frequencies and two amplitudes were covered by this study. These are shown in Table III-A-1. Amplitude is shown in inches, double amplitude, or total vertical displacement is shown below each amplitude, frequencies are in cycles per second, and the peak acceleration corresponding to each combination of frequency and amplitude is shown in G's in the right hand column.

The source of vibration was a mechanical shake table driven by an electric motor. Amplitude was adjusted by setting the eccentricity of four cams which link the table to two parallel drive shafts, while frequency was adjusted by varying the speed of the motor (see Fig. III-A-1). The subjects were seated in a non-damping wood and steel chair with backrest, but no arm support and no padding. A problem display panel was mounted on the shake table at an angle to permit comfortable viewing by the seated subject. A control column, attached to the shake table just in front of the chair, extended upward from the floor to a level between the subject's knees. A partition, which enclosed three sides of the shake table, served the purpose of screening off distractions from the subject's visual field. An emergency vibration cut-off switch was mounted on the wall of this partition within easy reach of the subject's right hand.

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*To be published in Journal of the Aerospace Medicine Association. Thesis from which this report was taken is appended.

TABLE III-A-1
Vibration Levels

Amplitude (inches)	Frequency (cps)	Peak Acceleration (g's)
A_1 = 0.065	f_1 = 2	0.03
(D.A. = 0.13)	f_2 = 4	0.10
	f_3 = 6	0.23
	f_4 = 8	0.41
	f_5 = 11	0.77
	f_6 = 15	1.44
A_2 = 0.13	f_1 = 2	0.05
(D.A. = 0.26)	f_2 = 4	0.20
	f_3 = 6	0.46
	f_4 = 8	0.82
	f_5 = 11	1.55
	f_6 = 15	2.88

The problem, as presented to the subject, consisted of a light moving continuously over the entire face of the display panel in a constantly changing, cyclic pattern. This effect was achieved by feeding the outputs of two sine wave signal generators at right angles to each other, to a display board, consisting of concentric squares of colored light bulbs. The two signals were set at the same amplitude, but at slightly different frequencies so that the tracking pattern changed continually and at a constant rate. The bulb which was lighted at any given instant was that one nearest the intersection of the two sine wave signals. A central white light represented the point where the resultant electrical signal was equal to zero in both the lateral axis and the to and fro axis of the board.

SHAKE TABLE (DIAGRAMMATIC)

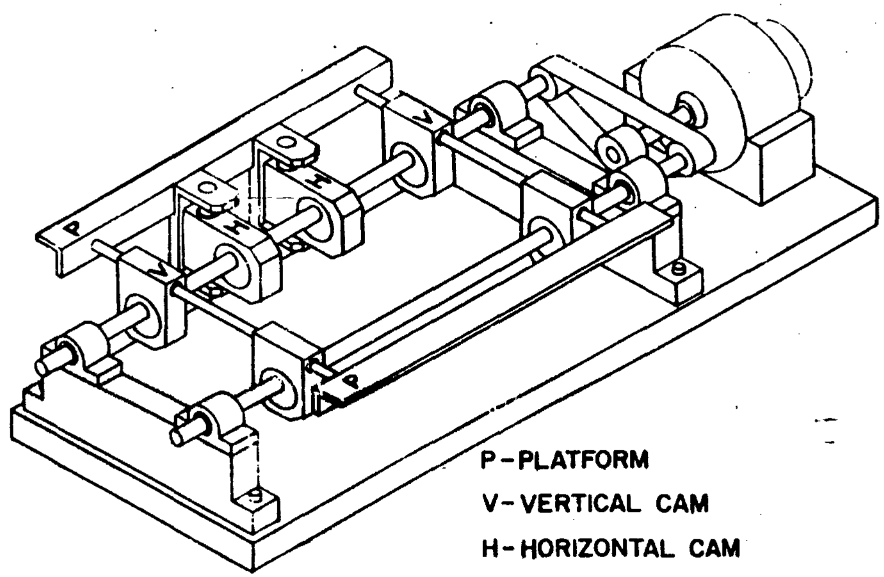


Fig. III-A-1

The subject's task was to maneuver the control stick in such a fashion as to neutralize the input signal from the problem and keep the central white light lit at all times. The control stick was activated and deactivated by a remote toggle switch. The subject's performance of the tracking task was recorded by an analog computor which measured the error in terms of the integral of the distance the light was away from the central neutral position with respect to time. This error score was automatically summed over a 58-1/2-second time period whenever a scoring button on the computor was pressed.

In this study, it was decided to require the subject to perform the task for two five-minute intervals of time, while experiencing continuous vibration for 20-minutes. The time profile of a single experimental run is shown in Fig. III-A-2. During each five-minute driving session, the subject's error was sampled twice. At each experimental session, the subject served as his own control by performing the task for two five-minute periods before his vibration exposure. Conditions during the control period were kept, as nearly as possible, identical to conditions during the vibration period so that the only significant change in the subject's environment was the presence of the vibration stress. A five-minute rest period was provided between the 20-minute control session and the 20-minute vibration session.

In order to evaluate the effect of repeated trials of the task and the effect of the period of time over which the subject was required to devote this attention to the task, each subject was subjected to a complete dry run near the mid-point of his series of vibration exposures. In this dry run, the full time profile was observed, but no vibration was employed.

Five subjects were selected for this study from a group of volunteers, all of whom were graduate students in the Department of Physical Education at The Ohio State University. Each subject was medically evaluated prior to his participation in the experiment. This evaluation included, in addition to a physical examination, a chest x-ray, an electrocardiogram, an upright film of the abdomen, and a urinalysis.

A physician monitored each run at more than four-cycles-per-second frequency and at the 0.13-inch amplitude. The subjects were encouraged at the onset of the experiment and prior to each of the more severe vibration profiles to stop the run at any time they experienced pain or any progressive discomfort or distress, whatever the nature.

2. Results

Each of the five subjects successfully completed the planned 20-minute exposure to every one of the 12 different levels of severity of vibration, although one subject discontinued the 0.13-inch, eight-cycle-per-second vibration run after 6-1/2-minutes, due to cramping

TIME PROFILE OF A SINGLE RUN

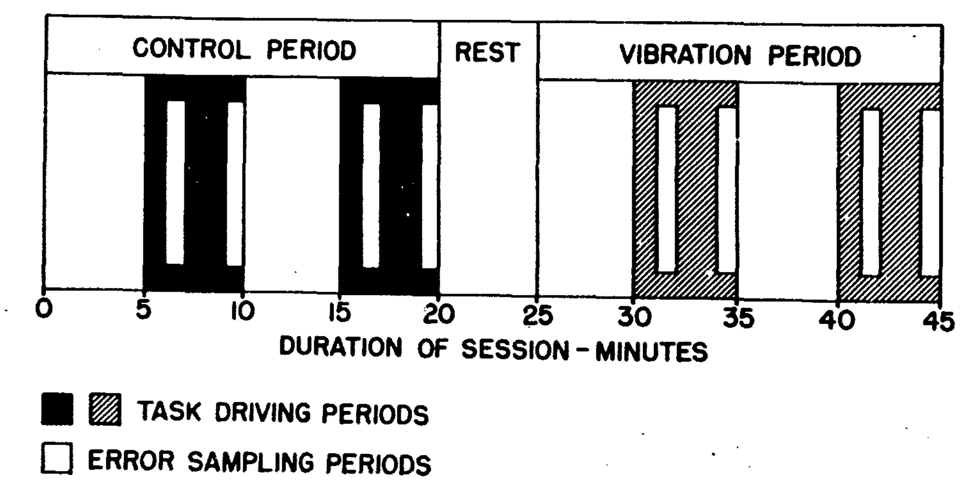


Fig. III-A-2

epigastric pain. At a later date, after he had finished the planned series, the subject repeated this vibration profile with no excessive discomfort.

All five of the subjects experienced discomfort to varying degrees of intensity at the 0.13-inch amplitude and at the frequencies of 6, 8, 11, and 15 cycles per second. The subjects all reported transitory abdominal, back, and chest pains during these more severe vibration exposures. In all instances, except that of the previously mentioned discontinued run, the subjects were able to obtain relief from any persistant pain by shifting posture in the chair.

Each of the five subjects achieved a consistent level of proficiency at the tracking task. This is illustrated by Table III-A-2, which shows the individual error score during each driving period of the dry run session. These results are typical in that, in general, each subject achieved repeated scores in the same order of magnitude and these scores tended to improve with successive trials.

Since the error scores obtained for each subject during the control period reflect the proficiency of the subject on that particular day, the difference between the error during the control period and the error during the corresponding vibration period was considered the net error score for that individual subject at each level of severity of vibration. Error score during the early part of vibration and during the last five minutes of vibration was recorded separately for purposes of comparison. The mean of the net error score for all five subjects (that is the average change in error between the control period and the vibration period) was then calculated for each separate condition of vibration. These average net error scores are shown in Table III-A-3.

Minus numbers indicated an improvement in tracking proficiency over the control period, while positive numbers show an increase in error as compared to the control period.

These results were subjected to an analysis of variance to test for significant differences between frequencies alone, between amplitudes alone, between the interaction of amplitude and frequency at each level of severity of vibration, and between early and late driving periods during each condition of vibration.

The summary of the analysis of variance is shown in Table III-A-4. As is shown in the right hand column of this table, changes in frequency are associated with significant changes in error score at the 1% level, as are changes in the interaction between amplitude and frequency, while changes in amplitude are associated with changes in score at a probability level of far less than 0.01%. Differences between the early and late driving time periods were not significant at these levels (7).

TABLE III-A-2

Individual Subject Performance Score During Each Task Driving Period of the "Dry Run" Session

Driving Period	Subjects				
	H.M.	D.B.	D.C.	J.K.	M.C.
1	343	597	687	519	662
2	360	593	818	570	711
3	343	553	613	512	772
4	330	549	645	454	645

calculated perfect tracking = 200

ineffectual tracking = 1410

TABLE III-A-3

Net Tracking Errors: Vibrating Scores Minus Control Scores at Each Level of Vibration (Mean of Five Subjects)

Amplitude	Frequency	Net Error/Time Period 5-10 min.	15-20 min.
0.06"	2 cps	-66	-66
	4 cps	-42	-51
	6 cps	-72	-72
	8 cps	-40	-57
	11 cps	-80	-112
	15 cps	-54	-63
0.13"	2 cps	+25	+46
	4 cps	-18	+2
	6 cps	+44	+48
	8 cps	+106	+78
	11 cps	+26	+39
	15 cps	+30	-5

TABLE III-A-4

Summary of Analysis of Variance

Source of Variance	Degrees of Freedom	Sum of Squares	Mean Squares	"F"	d.f.	P.
Between Frequencies	5	7,396	1,479	7.99	N_1, 5 N_2, 12	0.01
Between the Interaction of Amplitude and Frequency	5	7,401	1,480		N_1, 5 N_2, 12	0.01
Between Amplitudes	1	59,601	59,601	322.0	N_1, 1 N_2, 12	< 0.0001
Between Time Periods	1	216	216	1.17	N_1, 1 N_2, 11	> 0.10
Error	11	2,309	185			
Total	23	76,653				

The consistency of this difference in amplitudes is shown graphically in Fig. III-A-3. The net tracking error at each amplitude is graphed by frequency. A decrease in error is shown at all frequencies of vibration at 0.06-inch. A substantial decrease in error also occurred during the latter trials of the dry run protocol, indicating that this improvement in tracking is a result of repeated trials rather than a product of the vibration exposure. At the 0.13-inch amplitude, however, tracking performance is shown to deteriorate at all frequencies.

3. Discussion

While it is clear that no principles of general applicability can be established by a small study with so many variables under observation, two facts stand out from the bulk of data with such distinctive consistency that they appear to merit attention despite the limitations of the study.

The first of these facts is that all five of the subjects presevered through 20-minute periods at 12 different levels of vibration severity, including levels of severity which are near reported limits of tolerance for firmly restrained subjects over shorter periods of time (25). Moreover, all five of these unrestrained subjects were able to perform a sensitive, two-dimensional tracking task in a constructive manner, even under the most severe conditions of vertical vibration.

The second significant fact is that, while the task performance of each of these subjects did deteriorate as the severity of the vibration increased, by far the most significant deterioration in performance occurred in association with the change in amplitude of the vibration, regardless of differences in frequency. The overwhelming statistical significance of the difference between amplitudes compared to that of differences between changes in other sources of variance strongly indicates that, at the levels of vibration studied, the ability to perform such a two-dimensional tracking task is a function primarily of the amplitude of vibration.

If this is true, equations relating the effective severity of a vibration experience to levels of acceleration cannot be valid since acceleration is proportional to the product of amplitude times frequency squared. Functions of acceleration must, therefore, reflect changes in frequency to a far greater extent than they do changes in amplitude. These data, on the other hand, indicate that any mathematical expression characterizing the severity of vibration in terms of the physical forces imposed, should recognize amplitude as the predominate contributing factor.

NET TRACKING TASK ERROR VERSUS LEVEL OF VIBRATION

(MEAN VALUES FROM PERFORMANCE OF FIVE SUBJECTS)

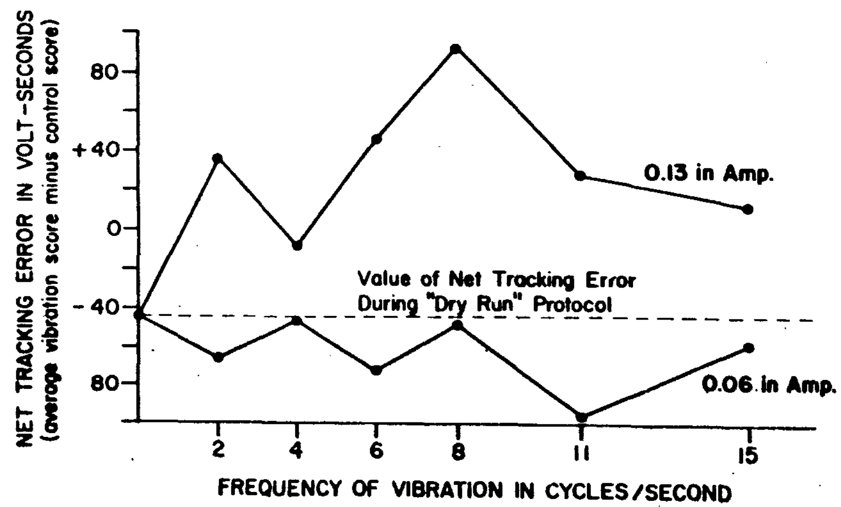


Fig. III-A-3

4. Summary

This study was carried out to clarify the relative importance of changes in frequency compared to changes in amplitude in determining the severity of whole-body vibration in the vertical plane. The ability of human operators to perform a difficult, two-dimensional tracking task at rest, and while vibrating, was compared as a measure of the effective severity of a given level of vibration.

Five volunteer subjects were each exposed to 12 levels of vibration, determined by six discrete frequencies and two amplitudes. Changes in proficiency of performance of the tracking task were electronically measured, and pooled results from the five subjects were subjected to an analysis of variance. Changes in performance were tested as they related to changes in frequency, changes in amplitude, changes in the interacting combinations of frequency and amplitude, and changes in duration of the vibration exposure.

Results of the analysis of variance showed that performance of the tracking task did change significantly as either frequency, amplitude, or both were varied. However, the significance of changes in task performance as related to changes in amplitude of vibration so overshadowed the level of significance of changes in performance when related to any other source of variance, as to indicate that amplitude is the variable of greatest importance in defining the severity of vibration under the conditions of this study.

It was felt noteworthy that all of these subjects were able to carry out the tracking task for the required time periods throughout each level of vibration severity, even though the most severe levels approximated subjective tolerance limits to vibration. Moreover, the tracking proficiency at the end of 20-minutes of continuous vibration was as accurate as that found after only five minutes of vibration at each level of severity.

B. OXYGEN CONSUMPTION DURING HUMAN VIBRATION EXPOSURE

The observations support the hypothesis that human subjects can tolerate relatively severe degrees of whole-body vibration and still function (4) if they are unrestrained and free to protect themselves. This protection is apparently a function of positioning the body and by voluntary and involuntary muscular guarding to dampen the vibration and reduce the transmission of stress to the vulnerable body areas. The exact location of the vulnerable areas has not been investigated, and from subjective experience the maximum response seems to vary with the frequency between 6-11 CPS depending on the individual body build. Despite the difference in frequency response, there appears to be similar types of discomfort produced in all subjects, the vibration tolerance being limited to a large extent by chest and abdominal pain.

The protective efforts induced by vibration result in an increase in metabolic activity which is strikingly reflected in the oxygen uptake ($\dot{V}_{O_2}$). At levels of 6-15 CPS, near the primary and secondary body resonant points, the increase in $\dot{V}_{O_2}$ is nearly linear with increasing frequency of vibration. The magnitude of increased metabloic load resulting from this effort, being less than double that of resting controls, while not extreme, is significant; and since it must be a constant effort, it is sufficiant to be a substantial contributor to fatigue in subjects exposed to vibration over extended periods. It is also evident that the increase in respiratory requirements must be considered when dealing with the problem of subjects in supplied or sealed environments.

Radke (26) suggested that 1 to 1-1/2 CPS would be a desirable seat frequency for improving truck ride characteristics. While this does seem to be a pleasurable ride, there is objective evidence of a sedative and somnolent effect produced by frequencies in this range. It may be that these low-frequency components are responsible for much of the subjective drowsiness occurring in persons exposed to vibrations of machinery and vehicles.

Finally, there appears to be an induced hyperventilation at 6 CPS, possibly as a result of the resonance of the abdominal organ mass producing diaphragmatic pressure, or alterations in respiratory mechanics induced by physical discomfort. The quantitative effect on alveolar carbon dioxide tension cannot be accurately evaluated since a steady base-line is not evident, and it is not certain that this hyperventilation could or would be maintained sufficiently long to produce respiratory alkalosis sufficient to contribute to impaired function.

The complete details of this study are appended to this report. A manuscript covering these data has been accepted for publication in the Aerospace Medical Journal.

C. RESPIRATORY FREQUENCY, TIDAL VOLUME, AND RESPIRATORY MINUTE VOLUME IN HUMAN SUBJECTS EXPOSED TO VERTICAL WHOLE-BODY VIBRATION

Whole-body vibration exposure leads to an increased metabolic demand for oxygen (Ernsting (11), Gaeuman (15), Hornick (18), Duffner and Hamilton (10)). It has been determined that the minute volume does not increase in direct proportion to the increase in oxygen consumption, but exceeds oxygen consumption to a considerable degree. Both Gaeuman (15) and Ernsting (11) have demonstrated altered respiratory quotients (RQ) which indicate hyperventilation. Hyperventilation during vibration may result from several mechanisms. The forces of vibration may act directly on the respiratory system (chest-lung) or on the abdominal viscera causing a mechanical pumping of air into and out of the lungs. Also it has been recently demonstrated that passive body movements, especially of the torso, may produce excess ventilation (Dixon, et al., (8)). It is also possible that the pain sometimes found in the chest and abdomen during whole-body vibration may lead to a hyperventilation phenomenon (19).

Several studies have been made of the passive and active mechanical characteristics of the chest-lung system in man. DuBois (9) and Brody (2) have studied this system using forced air oscillations, while Coermann (6) and his group used whole-body vibration. These studies essentially demonstrated that the resonant frequency of the abdomen and diaphragm is in the region of 3-4 CPS, while the chest-lung system resonates somewhere in the region of 7-11 CPS.

If the hyperventilation of vibration exposure is strictly related to mechanical factors, then one might expect the greatest degree of hyperventilation to occur in the region of resonance. If other factors are involved, then it is possible that the greatest degree of hyperventilation will occur in other regions of the frequency spectrum.

1. Methods

To obtain data on respiratory mechanics, the following data were collected on subjects exposed to vertical mechanical sinusoidal vibration in connection with performance and oxygen uptake studies. Five volunteer graduate students were subjected to vibration frequencies of 2, 4, 6, 8, 11, and 15 cycles per second, (CPS) at single amplitudes of 0.0625- and 0.125-inch. Acceleration "intensities" ranged from 0.03 to 2.88 G's. The subject was seated on a non-damping chair with no body restraint. Each subject was given a 20-minute control period in which he sat on the vibration table and all generators and motors were turned on, but vibration was not applied. During the second and fourth five-minute period the subject was required to monitor a psychomotor tracking task. A five-minute rest period was provided between the

control period and the vibration period. The vibration period was also 20-minutes long with the psychomotor task being applied at the same time intervals. Following the vibration period there was a 15-minute recovery period in which the subject quietly sat on the table.

Expired gases were collected through a modified Air Force type A-13A pressure breathing oxygen mask. The action of the valves were reversed so that inspiration took place through the expiration port, and exhaled air passed through the inspiration port to the hose normally used for the oxygen supply. This hose was attached to a one-way flap valve mounted on a ridged support which permitted flow away from the mask only. Following the valve in the expired air line were a "breath-through" cell from the Beckman LB-1 infra-red carbon dioxide analyzer and a differential pressure pneumotachograph from whence it went into two 120-liter spirometers. Smooth bore rubber tubing with an inside diameter of 1.25-inches was used throughout. The total resistance to expiration offered by the entire system was between one and two inches of water. Frequency and pattern were determined from the pneumotachograph recordings, and all volumes were determined from the displacement of the spirometers as recorded by kymographs. The expired gas was collected alternately in one spirometer and then the other for five-minute periods.

2. Results

a. Frequency

Respiratory frequency data are summarized in Table III-C-1. At only one level of vibration intensity was the respiratory frequency altered, and this was not statistically significant; namely, 15 CPS at 0.062-inch, or 1. [illegible]. All other respiratory frequencies were within the range of normal variation. It should be noted that there is a tendency for an increased respiratory rate during the time the subjects were monitoring the psychomotor tracking task. This was not a significant increase, but the consistency was remarkable at all but the lowest frequency-amplitude exposure.

b. Tidal Volume

In all exposures at 0.0625-inch amplitude, the tidal volume was not significantly altered. These values are listed in Table III-C-2. This finding was also true at 2 and 4 CPS at the 0.125-inch amplitude. A significant increase in tidal volume occurred at 6, 11, and 15 CPS at the higher amplitude. Tidal volume was more greatly increased by the 11 CPS vibration frequency, it being twice that of 6 and 15.

TABLE III-C-1. Respiratory Frequency
(Vibration from 20-40 min.
mean ± std. deviation)

Time	2 CPS	4 CPS	6 CPS	8 CPS	11 CPS	15 CPS
Amplitude .125 inches						
0-5	14.1 ± 1.4	15.2 ± 4.1	14.6 ± 2.9	14.2 ± 3.1	15.6 ± 3.2	15.6 ± 1.7
5-10	15.6 ± 2.8	16.0 ± 315	16.2 ± 317	15.6 ± 2.6	16.1 ± 3.2	16.6 ± 3.0
10-15	15.7 ± 2.5	15.5 ± 3.2	14.7 ± 3.3	14.0 ± 3.5	14.9 ± 3.1	15.7 ± 1.9
15-20	16.4 ± 3.3	17.2 ± 2.8	16.8 ± 3.3	15.6 ± 3.6	16.0 ± 2.9	17.1 ± 2.4
20-25	15.2 ± 2.3	17.7 ± 2.3	16.1 ± 3.9	15.2 ± 2.8	15.1 ± 2.1	18.3 ± 2.2
25-30	16.6 ± 2.4	18.2 ± 3.5	16.5 ± 3.1	17.4 ± 6.3	17.4 ± 6.0	21.3 ± 3.3
30-35	15.4 ± 2.2	16.8 ± 2.9	17.1 ± 4.4	16.2 ± 4.8	13.9 ± 2.8	19.7 ± 4.7
35-40	16.4 ± 2.2	18.5 ± 3.0	17.3 ± 2.4	19.0 ± 7.2	16.5 ± 5.4	21.1 ± 6.8
40-45	14.6 ± 2.5	14.8 ± 2.0	14.7 ± 2.2	14.6 ± 3.6	14.4 ± 2.9	16.2 ± 1.7
45-50	14.3 ± 2.2	14.8 ± 2.4	15.0 ± 2.7	14.8 ± 3.1	15.8 ± 2.5	16.8 ± 3.1
50-55	14.7 ± 2.8	14.2 ± 2.1	14.3 ± 2.7	13.4 ± 2.0	14.5 ± 2.9	14.6 ± 2.3
Amplitude .0625 inches						
0-5	16.0 ± 2.8	17.0 ± 4.8	17.4 ± 3.1	17.6 ± 4.6	18.0 ± 3.2	17.2 ± 3.0
5-10	21.0 ± 5.3	14.5 ± 3.4	16.2 ± 4.0	1[illegible].2 ± 2.3	14.4 ± 2.2	15.6 ± 3.0
10-15	17.3 ± 1.2	18.0 ± 3.7	15.6 ± 3.0	18.0 ± 3.2	18.0 ± 2.0	16.8 ± 3.6
15-20	18.6 ± 5.0	19.0 ± 4.2	16.8 ± 5.8	18.4 ± 3.3	17.6 ± 1.7	16.4 ± 2.6
20-25	16.0 ± 4.0	17.0 ± 3.5	18.4 ± 5.5	20.0 ± 4.0	21.2 ± 4.8	22.0 ± 7.9
25-30	18.5 ± 4.1	15.0 ± 2.6	16.6 ± 4.4	17.2 ± 3.3	16.4 ± 0.9	18.0 ± 3.7
30-35	19.5 ± 3.4	18.0 ± 3.6	18.2 ± 4.6	20.8 ± 4.4	20.4 ± 5.0	20.8 ± 3.6
35-40	19.8 ± 6.2	19.0 ± 2.6	18.4 ± 3.6	21.6 ± 4.6	22.4 ± 6.2	19.6 ± 6.1
40-45	15.3 ± 3.1	15.0 ± 2.6	13.6 ± 2.6	14.4 ± 1.7	16.4 ± 3.0	15.6 ± 2.6
45-50	14.7 ± 2.3	13.3 ± 4.2	12.6 ± 1.9	14.4 ± 2.2	13.2 ± 2.3	15.2 ± 2.3
50-55	16.5 ± 3.4	15.0 ± 1.0	14.6 ± 2.2	15.6 ± 2.6	15.6 ± 2.6	14.0 ± 4.0

TABLE III-C-2. Tidal Volume-Stpd
(Vibration from 20-40 min.
mean ± std. deviation)

Time	2 CPS	4 CPS	6 CPS	8 CPS	11 CPS	15 CPS
	Amplitude .125 inch					
0-5	541 ± 66	598 ± 126	548 ± 90	615 ± 68	618 ± 138	552 ± 116
5-10	492 ± 123	567 ± 124	507 ± 91	546 ± 71	524 ± 64	519 ± 111
10-15	530 ± 86	585 ± 131	574 ± 58	626 ± 119	607 ± 78	590 ± 90
15-20	461 ± 125	509 ± 69	464 ± 87	569 ± 88	528 ± 88	513 ± 79
20-25	542 ± 110	542 ± 91	589 ± 122	679 ± 99	817 ± 109	671 ± 180
25-30	498 ± 82	484 ± 95	559 ± 86	669 ± 153	800 ± 317	603 ± 172
30-35	517 ± 90	548 ± 110	557 ± 138	685 ± 71	916 ± 183	631 ± 176
35-40	418 ± 126	471 ± 105	557 ± 71	612 ± 85	833 ± 254	607 ± 203
40-45	521 ± 119	552 ± 69	486 ± 74	551 ± 97	601 ± 151	559 ± 105
45-50	460 ± 93	487 ± 103	476 ± 99	505 ± 91	466 ± 73	472 ± 127
50-55	518 ± 99	509 ± 66	529 ± 75	586 ± 65	542 ± 120	528 ± 176
	Amplitude .0625 inch					
0-5	558 ± 89	444 ± 80	459 ± 78	484 ± 93	467 ± 89	512 ± 36
5-10	503 ± 35	651 ± 269	546 ± 125	557 ± 81	578 ± 77	544 ± 93
10-15	517 ± 172	451 ± 39	518 ± 64	481 ± 48	432 ± 98	521 ± 116
15-20	443 ± 121	472 ± 51	530 ± 115	466 ± 22	458 ± 76	499 ± 64
20-25	387 ± 94	466 ± 116	504 ± 124	410 ± 60	433 ± 161	435 ± 56
25-30	443 ± 159	592 ± 140	513 ± 117	540 ± 81	483 ± 123	539 ± 76
30-35	488 ± 95	471 ± 51	422 ± 66	419 ± 66	407 ± 98	482 ± 85
35-40	416 ± 133	477 ± 77	453 ± 40	433 ± 21	383 ± 215	503 ± 108
40-45	416 ± 132	569 ± 154	568 ± 109	519 ± 13	452 ± 104	483 ± 85
45-50	480 ± 116	658 ± 196	557 ± 75	530 ± 143	538 ± 106	459 ± 52
50-55	384 ± 135	528 ± 18	496 ± 105	485 ± 88	452 ± 27	543 ± 168

c. Minute Volume

Minute volume, being the product of respiratory frequency and tidal volume, should be the most sensitive indicator of changes in respiratory mechanics. At .0625-inch amplitude, 15 CPS shows a slight increase in minute volume (Fig. III-C-1). Figure III-C-2 shows the results for the .125-inch amplitude. At vibration frequencies of 6 and 8 CPS, a 20% increase in minute volume can be observed, and 11 and 15 CPS yield a 50% rise in minute volume.

Correlation of minute volume with various functions of amplitude and frequency tend to point out the amplitude dependency of this particular physiological response to whole-body vibration. Table III-C-3 lists the regression equations and the correlation coefficients for minute volume vs acceleration (inches/sec^2), velocity (inches/sec), and the function derived by Fraser (14), (amplitude times the square root of frequency). All correlation coefficients are very high indicating that minute volume correlates well with each of the above functions. There is a curious inverse relationship between the power of the vibration frequency and the correlation coefficient; the lower the power of f, the higher the correlation.

d. Subjective Responses

Each subject listed his subjective sensations, in his own words, after each run. Table III-C-4 lists the incidence of chest and abdominal pain among the subjects of this study. At both amplitudes the most severe frequencies were 11 and 15 CPS in terms of these symptoms. These were the frequencies at which minute volume altered to the greatest degree.

e. Oscillatory flow

At all vibration frequencies above 2 CPS, expiratory flow patterns obtained by the pneumotachograph showed a large degree of oscillatory flow. This was not an artifact induced by pumping action of the connecting tubing. Figure III-C-3 shows a representative tracing of these patterns. There is no inspiratory flow pattern as normally seen in pneumotachograms because of the one-way valve in the line. A crude attempt to evaluate the degree of oscillatory flow was made by comparing the peak rate of flow with the peak rate of flow induced by the oscillation. Figure III-C-4 shows the data obtained from the tracings of one subject. The peak flow velocity at 2 and 4 CPS was not different during the vibration period as compared to the control period. At 4 CPS, however, the oscillatory flow was 67% of the inspiratory flow. The peak inspiratory velocity increased with increasing vibration frequency up to 11 CPS, and then fell sharply at 15 CPS. The oscillatory flow velocities were almost equal to the peak inspiratory velocity. Again at 15 CPS the ratio between the two indicated that the oscillatory flow had dropped to about 60% of the inspiratory flow.

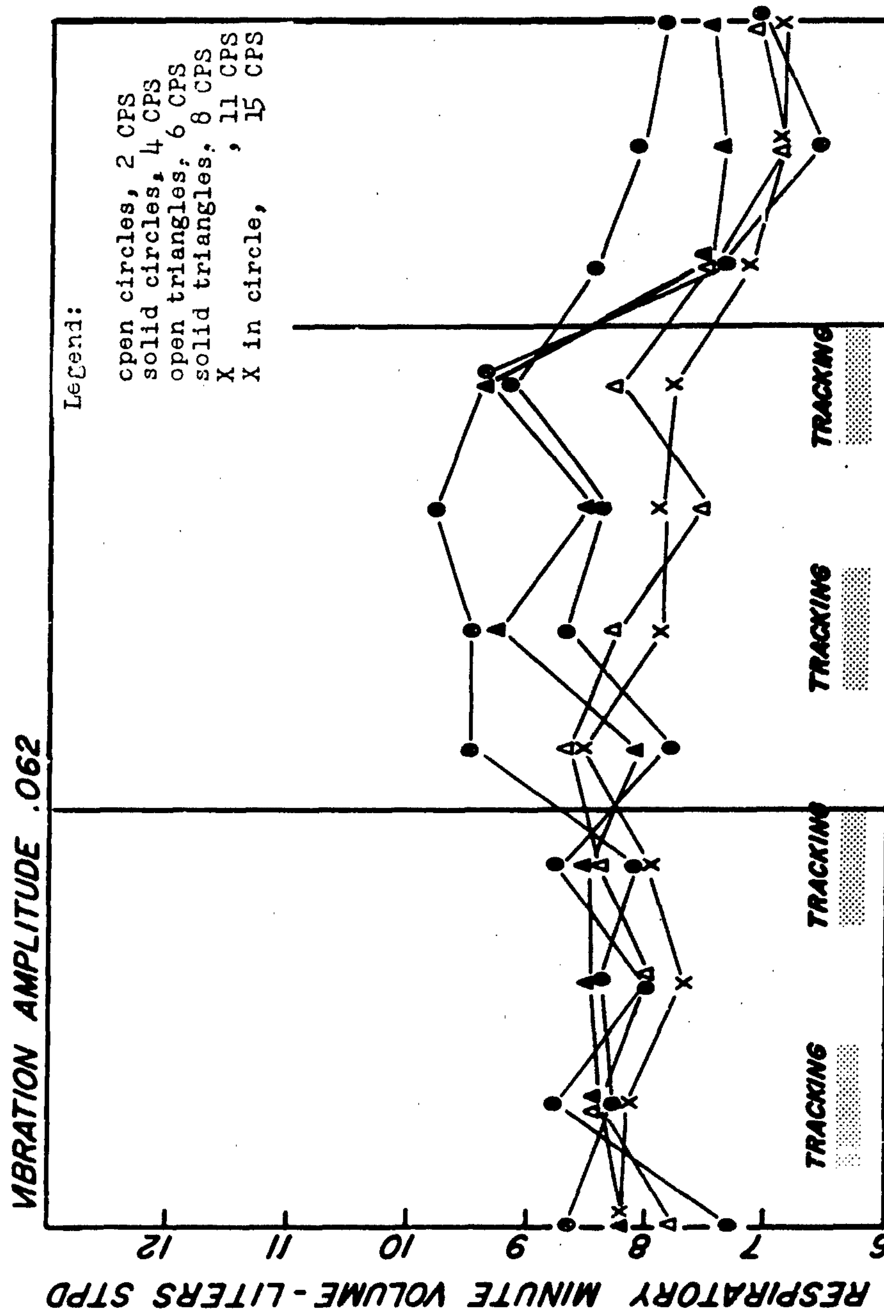

VIBRATION AMPLITUDE .062
RESPIRATORY MINUTE VOLUME - LITERS STPD
6
7
8
9
10
11
12
5
10
15
20
25
30
35
40
45
50
TRACKING
TRACKING
TRACKING
TRACKING
Legend:
open circles, 2 CPS
solid circles, 4 CPS
open triangles, 6 CPS
solid triangles, 8 CPS
X , 11 CPS
X in circle, 15 CPS

Fig. III-C-1

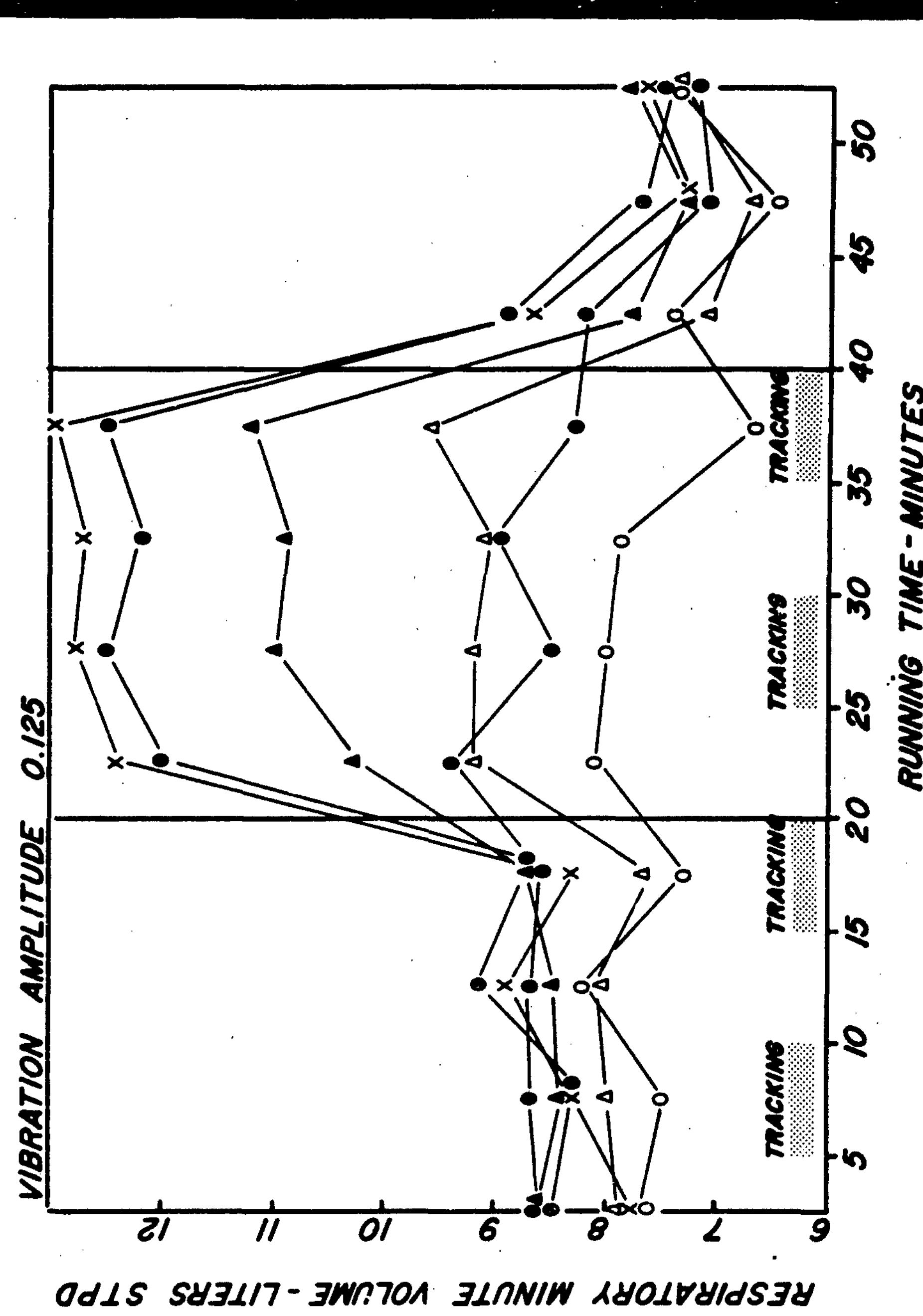

VIBRATION AMPLITUDE 0.125
TRACKING
TRACKING
TRACKING
TRACKING
RESPIRATORY MINUTE VOLUME - LITERS STPD
6
7
8
9
10
11
12
5
10
15
20
25
30
35
40
45
50
RUNNING TIME - MINUTES

Fig. III-C-2

TABLE III-C-3
Regression and Correlation
(minute volume s " ntensity")

Intensity	Regression		Correlation Coeff.
Acceleration af^2 (in/sec^2)	af^2	$= 3.2 + .036\ \dot{V}$	0.800
Velocity af (in/sec)	af	$= 2.09 + .025\ \dot{V}$	0.885
Time-displacement af-1/2 (in/sec)	$af^{\frac{1}{2}}$	$= 0.43 + .0059\ \dot{V}$	0.901

TABLE III-C-4
Subjective Pain

A	F	Chest Pain	Abdominal Pain	Unpleasant
1/16	2			
	4			
	6			1
	8			
	11	1	2	
	15	1	1	
1/8	2			
	4			
	6		1	
	8	2	1	1
	11	3	3	3
	15	2	2	4

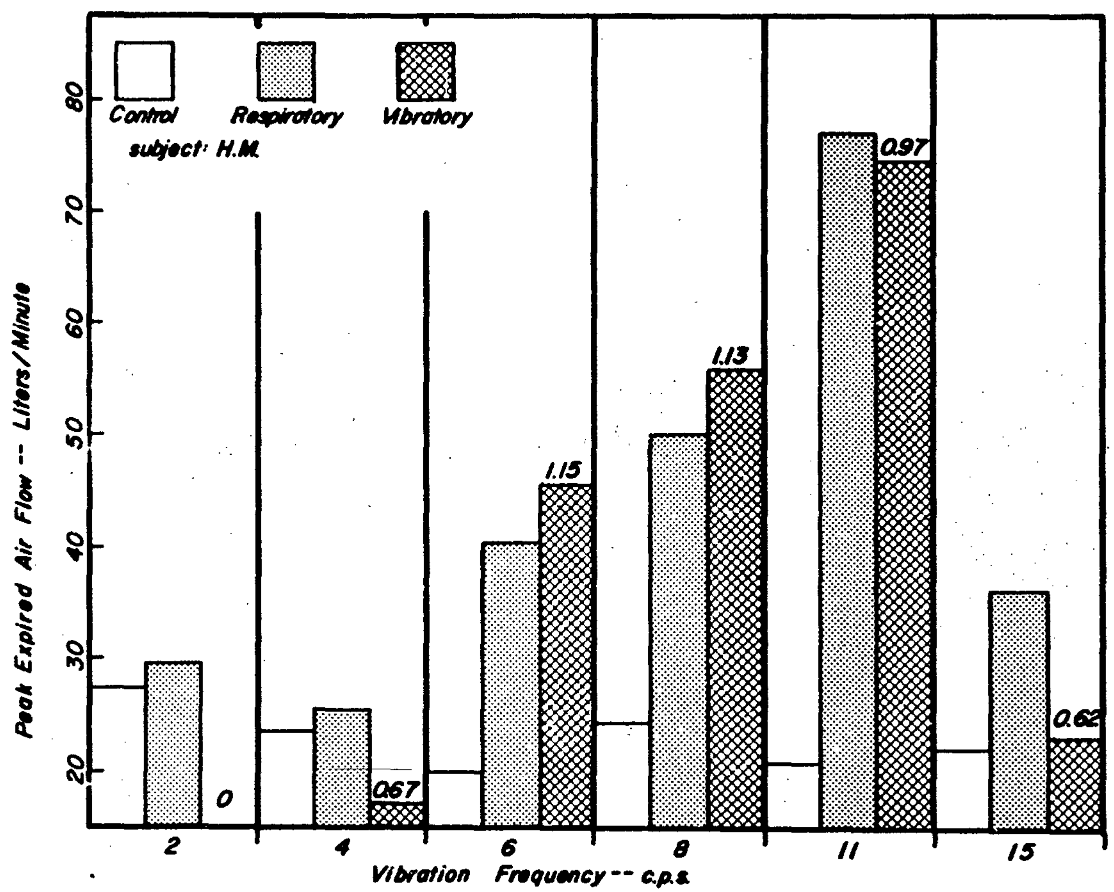

Control
Respiratory
Vibratory
subject: H.M.
Peak Expired Air Flow -- Liters/Minute
80
70
60
50
40
30
20
0
0.67
1.15
1.13
0.97
0.62
2
4
6
8
11
15
Vibration Frequency -- c.p.s.

Fig. III-C-3

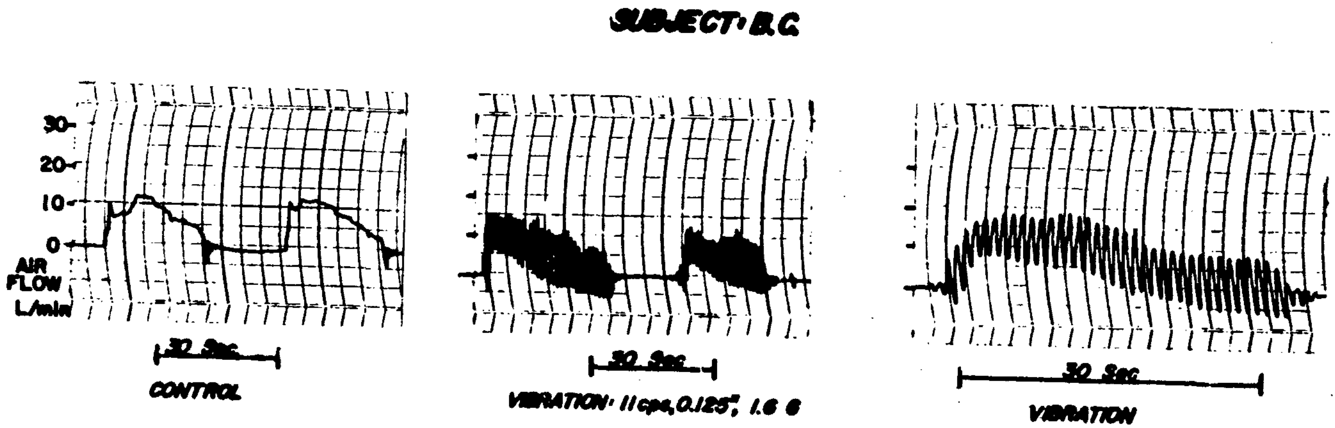


Fig. III-C-4. Representative Pneumotachograph

f. Carbon dioxide in expired air

Table III-C-5 lists the average carbon dioxide found in the mixed expired air of the subjects at rest, during vibration, and during recovery. Because of the position of the carbon dioxide sample cell in the expired circuit, a true "end tidal sample" could not be obtained. Sufficient mixing had occurred by the time the air mass reached the pickup head for this to be impossible, however, a mixed expired carbon dioxide concentration was obtained. Tracings above 6 CPS in the 0.125-inch amplitude contained too much artifact to be reliable.

From the data presented in the table it should be obvious that there is no essential difference in mixed expired CO_2 concentration.

3. Discussion

From the data presented here, one thing is obvious, and that is that the minute volume attained during certain intensities of whole-body vibration greatly exceeds that which is required to supply the extra oxygen demand imposed by the vibration exposure. Since the respiratory frequency is not drastically altered, it must be concluded that all, or almost all, of the extra air volume is derived from an increase in tidal volume. By what mechanism can this be accomplished? No doubt there is an increased depth of respiration in relation to the increased oxygen demand. It would seem logical to assume that the extra tidal air is derived by mechanical forcing of the diaphragm and the abdominal contents working on the chest-lung system. If this were true, then one might expect the greatest changes in tidal volume in the vibration frequency range of 3-4 CPS, which is the resonant frequency of the diaphragm and viscera.

On the contrary, the data here seem to indicate that the greatest tidal volume changes occur at the frequency of 11 CPS at the higher amplitude. This fact would appear to be related to the chest resonant frequency as opposed to action of the diaphragm (DuBois, et al., 9). Indirect support for this reasoning can be obtained from the subjective complaints of the subjects. No pain in the chest or abdominal region was experienced at 4 CPS. Most of the reported pain occurred at 11 CPS. One should not fall into the trap of excluding the diaphragm from this response on the basis of these data alone. The 3 CPS frequency was not included in this study, a most unfortunate lack of foresight, and, hence, any effects arising from resonance in this system may have been missed completely. On the other hand, the resonance of the diaphragm is usually listed as being between 3 and 4 CPS, so some effect should have been observed at the latter frequency. However, the ventilatory response to 4 CPS at both amplitudes was absent.

TABLE III-C-5
Percent CO_2 in Mixed Expired Air
(mean ± S.D.)

A.	F.	Control	Vibration	Recovery
.062	4	3.01 ± .44	2.74 ± .24	3.04 ± .55
	6	2.51 ± .34	2.44 ± .33	2.53 ± .31
	8	2.86 ± .29	2.67 ± 1.58	2.80 ± .33
	11	2.66 ± .27	2.57 ± .37	2.70 ± .29
	15	2.74 ± .33	2.63 ± .32	2.68 ± .37
.125	2	2.96 ± .20	3.00 ± .57	2.75 ± .19
	4	3.05 ± .20	2.93 ± .25	3.07 ± .29
	6	2.91 ± .27	2.76 ± .31	2.90 ± .31
	All Control	2.83 ± .34		

Since the greatest occurrence of pain in the chest happened at the frequency of resonance for the chest-lung system, it may be impossible to separate the effects of pain and thoracic resonance on the tidal volume. One fact may give us a clue, though, and that is that, while pain usually leads to increased pulmonary ventilation, it also leads to an increased respiratory rate (Houssay, et al., 19). Since the respiratory frequency was only slightly elevated at 15 CPS and 0.125-inch, it is highly probable that pain as such does not play an important role in the ventilatory response to vibration.

More evidence for the thesis that the ventilatory response to vibration is purely mechanical can be obtained from studying the pneumotachograph tracings. The effect of the vibration can be clearly seen superimposed on the respiratory pattern. It would appear that, as long as the airway is open, the air is forced in and out in rhythm with the vibration frequency (phase relations were not determined). The amplitudes of the air oscillations were greatest near the end of expiration, and at 8 and 11 CPS were equal to the amplitude of the peak expiratory flow. This phenomenon occurred at all frequencies except 2 CPS in both amplitudes.

The carbon dioxide data were somewhat disappointing. Both Gaeuman (15) and Ernsting (11) have demonstrated altered RQ's indicating hyperventilation. Ernsting (11) has also measured end-tidal CO_2

tensions in expired air and also arterial CO_2 tension. These data very strongly indicate that hyperventilation is a result of vibration exposure. However, our data did not indicate that the mixed expired CO_2 tensions were significantly altered. This was true even at levels where Ernsting (11) has found altered end-tidal and arterial levels. The reason for this descrepancy is not apparent at present.

An effort was made to relate the ventilatory response observed in these studies to amplitude-frequency functions. Correlation with acceleration, velocity, and af[illegible] were all high. The highest correlation coefficient was obtained with the lowest power of frequency, indicating that the response is primarily amplitude related. This is in agreement with Fraser (14), and Catterson (4) who have found similar relationships with psychomotor performance data, and with Reiher and Meister (28) using subjective reactions. Although the amplitude range was not large, it would appear that the 0.0625-inch amplitude might be below an "amplitude threshold," while the 0.125-inch amplitude would be above it. This is a matter that needs serious consideration in the future.

4. Conclusions

Minute volume is related to the "intensity" of vibration, irrespective of how intensity is expressed. The increase in minute volume is accomplished through an increased tidal volume, respiratory frequency remaining relatively constant. It is proposed that this increase in tidal volume is related to the mechanical forces of vibration, and does not represent any significant physiological control over the ventilation.

D. SKIN RESISTANCE (PSYCHO-GALVANIC RESPONSE) DURING WHOLE-BODY VIBRATION

Skin resistance has long been used as a measure of sub-cortical activation of the nervous system (Rothman (29), Wang (34), Goodby (16), and Levy (22)). Since sympathectomy abolishes this response, it has been assumed that a decrease in skin resistance is a measure of increased activity of the sympathetic nervous system (Goodby, 16).

The response of the human to whole-body vibration does not appear to elicit gross physiological effects which can be measured easily. Because of the sensitivity of the skin resistance measurement, it was felt that perhaps it would indicate any small degree of sympathetic activation which may occur in individuals subjected to whole-body mechanical vibration.

1. Methods

Subjects selected from a volunteer group for studies of psychomotor performance and gas metabolism were instrumented for skin resistance. Silver disc electrodes, 8 mm in diameter, were coated with saline electrode paste and taped to the dorsal and ventral aspects of the left foot. A 50-micron-amp current was supplied by a Grass 5P1 low-leveled D. C. amplifier (chopper stabilized) which also served as the measuring system. This circuit is so designed as to yield a one-millivolt signal for each 10,000 ohms resistance.

The subjects were required to sit on the vibration table for a 50-minute period. The first 20-minutes of this period served as a subject control period. The psychomotor tracking task was monitored for the second and fourth five-minute periods. The second 20-minute period was identical to the first with vibration being applied to the subject. The final 10 minutes was used as a recovery period and no psychomotor monitoring was required. Expired gas was collected during the entire 50 minutes.

Two amplitudes of vibration, 1/16- and 1/8-inch, were used with frequencies of 4, 6, 8, 11, and 15 cycles per second. Five subjects were used, but for any given frequency-amplitude pair at least one signal failed and frequently more. Only data for frequency-amplitude combinations with satisfactory data for three or more subjects were used in the analysis.

2. Results

Because of the large variability, both between and within subjects, all data are expressed as a percentage change. The end of the 20-minute control period (t_{20}) was arbitrarily chosen as the

reference point, i.e., t_{20} = 0% change. Table III-D-1 lists these data for each frequency-amplitude combination. The control skin resistance levels were highly variable, partially due to the small number of subjects. However, the variability of the percentage change decreased during and after vibration.

No consistent relationship between the percent change in skin resistance and frequency, amplitude, or acceleration could be determined ($r = .389$). Consequently all data were combined and the total results are given graphically in Fig. III-D-1. Table III-D-2 lists the T and P values for these data. The data in Fig. III-D-1 indicate a significant and consistent decrease in skin resistance which occurs immediately with the onset of vibration. Also periods of monitoring the psychomotor tracking task tended to produce a further decrease in skin resistance.

3. Discussion

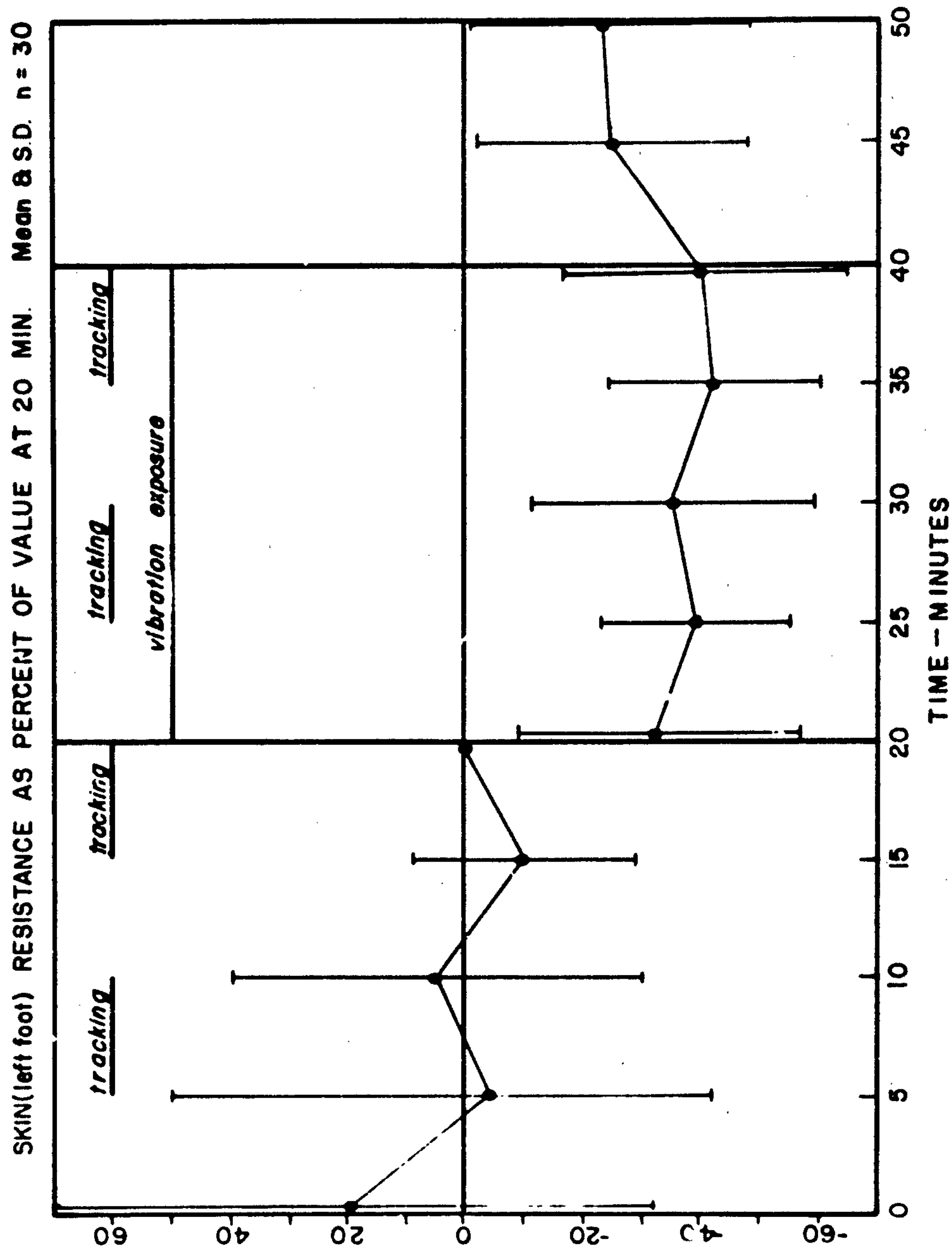
Whole-body vibration appears to be a significant stimulus to elicit changes in skin resistance. The response was not maximal, however, as psychomotor monitoring tended to produce a further response. In one instance, when the subject "lost" the tracking task during vibration, there was a further and marked decrease in skin resistance at this time.

It was quite surprising to find no relationship between the degree of response and vibration intensity, regardless of how intensity is expressed. This fact would tend to indicate that the subject cannot fully differentiate between the levels of vibration employed. It would appear that anxiety and/or apprehension played a large role in the skin resistance changes observed in this study.

Skin resistance does represent a measurement sensitive enough to respond to the physiological stress of whole-body vibration. Further refinements are needed to render these data more functional.

TABLE III-D-1
GSR Summary
Vibration from t_{20} min. to t_{40} min.

1/16-inch amplitude 1/8-inch peak to peak					1/8-inch amplitude 1/4-inch peak to peak				
	Time	GSR % t_{20}	S. D.	SE.		Time	GSR % t_{20}	S. D.	SE.
4 CPS	0	44.6	±103.0	59.2	4 CPS	0	10.0	± 8.8	5.1
N = 3	5	16.3	103.0	59.2	N = 3	5	-35.2	30.6	17.6
	10	- 8.1	101.5	58.3		10	22.2	36.0	20.7
	15	-15.4	25.0	14.4		15	-23.0	23.7	13.6
	21	-47.2	27.4	15.7		21	-37.6	38.6	22.2
	25	-53.5	33.6	19.3		25	-37.2	19.4	11.2
	30	-48.5	34.4	19.8		30	-14.8	30.7	17.6
	35	-59.6	13.5	7.8		35	-38.3	27.7	15.9
	40	-55.7	33.1	19.0		40	-22.6	23.9	13.7
	45	-17.6	1.8	1.2		45	- 8.7	34.2	20.0
	50	- 9.5	3.6	2.7		50	-17.9	42.6	24.5
6 CPS	0	8.0	+ 17.9	8.9	6 CPS	0	- 4.3	± 22.9	13.2
N = 4	5	- 7.0	- 23.1	11.6	N = 3	5	- 6.1	25.6	14.7
	10	5.1	16.9	8.5		10	0.9	6.2	3.5
	15	-11.2	14.6	7.3		15	- 2.5	9.0	5.1
	21	-26.9	13.7	6.9		21	-14.4	12.9	7.4
	25	-36.2	22.1	11.0		25	-34.5	26.6	21.0
	30	-35.3	15.4	7.7		30	-38.5	29.8	17.1
	35	-37.0	13.5	6.8		35	-40.3	26.4	15.2
	40	-35.7	17.2	8.6		40	-35.2	29.6	17.0
	45	-26.0	14.1	7.0		45	-30.5	21.9	12.6
	50	-26.0	14.1	7.0		50	-27.7	17.6	10.1
8 CPS	0	15.5	± 39.8	19.9	11 CPS	0	61.9	±107.9	62.0
N = 4	5	- 8.8	56.1	28.0	N = 3	5	14.5	26.3	15.1
	10	13.0	33.4	16.7		10	45.9	71.6	41.1
	15	-10.3	21.8	10.9		15	- 0.1	11.4	6.6
	21	-19.9	30.7	15.4		21	-31.0	16.8	9.7
	25	-31.5	29.4	14.7		25	-47.6	8.7	5.0
	30	-25.2	30.4	15.2		30	-37.9	16.1	9.2
	35	-33.0	29.7	14.8		35	-45.7	11.1	6.4
	40	-26.9	29.8	14.9		40	-53.6	13.8	7.9
	45	-30.5	28.8	14.4		45	-34.5	11.5	6.6
	50	-27.0	28.6	14.3		50	-30.4	13.0	7.5
15 CPS	0	15.4	± 6.4	3.6	15 CPS	0	-15.9	± 26.8	15.4
N = 3	5	- 5.0	15.0	8.6	N = 3	5	-30.5	36.0	20.7
	10	5.5	3.7	2.1		10	- 9.7	8.5	4.9
	15	- 2.2	12.4	7.7		15	-21.4	14.1	8.1
	21	-24.4	26.2	15.1		21	-56.1	11.5	6.6
	25	-27.4	31.0	17.8		25	-56.7	15.3	8.8
	30	-31.9	27.3	15.7		30	-52.7	20.9	12.0
	35	-33.8	26.8	15.4		35	-56.9	15.5	8.9
	40	-29.4	18.7	10.7		40	-60.6	9.7	5.6
	45	-18.6	12.3	7.1		45	-13.3	44.0	25.3
	50	-31.9	19.1	11.0		50	- 8.6	53.2	30.6



SKIN(left foot) RESISTANCE AS PERCENT OF VALUE AT 20 MIN. Mean & S.D. n = 30
tracking
tracking
tracking
tracking
vibration exposure
PERCENT DIFFERENCE
60
40
20
0
-20
-40
-60
0
5
10
15
20
25
30
35
40
45
50
TIME — MINUTES

Fig. III-D-7

TABLE III-D-2

T and P Values For All Skin Resistance Data N = 30
(difference from t_{20} ie. 0%)

Time	T	P
0	2.05	.05
5	0.44	.05
10	0.82	.05
15	2.91	.01
21	7.41	.01
25	13.10	.01
30	7.89	.01
35	12.24	.01
40	8.98	.01
45	5.83	.01
50	5.36	.01

E. BODY SURFACE RESPONSES OF STANDING MALE SUBJECTS SUBJECTED TO VERTICAL VIBRATIONS

1. Introduction

When the unrestrained human body is subjected to forced vibration, the body, as a whole, vibrates, its constituent parts vibrate and the body responds physically to the forcing vibration in a characteristic fashion which is dependent upon:

1. The direction of vibration (vertical, horizontal, etc.)

2. The kind of vibration (sinusoidal, triangular, etc.)

3. The intensity of vibration (frequency and amplitude)

4. The physical posture of the subject (standing, seated, etc.)

5. The muscular tone control of the subject's body. (Relaxed, tense.)

6. The subject's body build and physical condition.

7. The subject's ability to control response by standing defensively, i.e. knees bent, weight on toes, etc.

When force vibrated through certain frequency amplitude ranges, the human body and its parts exhibit resonance characteristic of a complicated structural entity made up of elements having diverse elastic and dampening characteristics.

The outward patterns of general dynamic response of individuals of comparable mass, body build and physical condition are quite similar. Whether this similarity exists for the internal parts of the human body is a question of interest and importance.

Certain physiological responses (vision, eye resonance) of the human body are directly related to outwardly apparent dynamic responses. Other physiological responses, especially those manifesting stress, obviously are modified by intermediate mechanisms of various complexities. That certain of the responses appear quite complex is not surprising since they can and probably do (at high vibration intensities) involve neurological, physiological and psychological mechanisms.

Two basic mechanical stress-producing situations seem possible. First is the stress produced and associated with the energy absorption brought about by the dynamic response of an individual part, which has reasonably homogenous elastic and dampening characteristics, and second, the stress produced in, say, the tissue connecting two or more such parts which have dissimilar elastic and dampening characteristics. The first type would be expected to be directly related to the conventional measures of vibration response (impedance, etc.), the second, possibly to a differential relationship of conventional measures for two or more parts. Bone, body fluids, and discrete tissue can all be involved. Interference with certain normal physiological functions, both by direct physical interference and neurological feed back, would appear likely.

From the above considerations, it seems possible that many of the subjective, physiological and psychological responses observed but unexplained, originate from physical dynamic responses in part understood but not located.

It is suggested that, because of its first order importance, the physical dynamic response aspect of the over-all human vibration response problem should be consolidated, expanded, and critically reviewed from the standpoint of (1) more clearly understanding and describing its primary actions, and (2) testing and establishing its relationship to other responses. As a first step, we have started to present study which is an attempt to describe the outward (surface) responses of the human body to tolerable sinusoidal vibration intensities of amplitudes from 1/16- to 5/16-inch and frequencies from 2 to 15 cycles per second (CPS). Data have been obtained and are being analyzed for standing male subjects subjected to vertical sinusoidal vibration. Our protocol calls for another experiment for seated subjects, similar studies for standing and seated subjects subjected to horizontal fore and aft, and lateral vibrations.

It is believed that the photographic technique employed for this study can be applied, utilizing x-ray, to the study of internal organs and parts. This study is contemplated.

The results of these studies and others of physiological and psychological nature will be compared and combined where indicated.

2. Experimental Procedure

Each of eight male human (students) subjects of athletic build, between the ages of 19 and 31 years, were subjected, while standing, to the following sinusoidal vertical vibration intensities:

Amplitudes (nominal)	Frequencies
1/16"	2,3,4,5,6,7,8,9,10,11,12,13,14,15
1/8	2,3,4,5,6,7,8,9,10,11,12,13,14,15
3/16	2,3,4,5,6,7,8,9,10
1/14	2,3,4,5,6,7,8,9
5/16	2,3,4,5,6,7,8

Prior to vibration, various points of the subject's body were marked with a white spot on a black background, as shown in Figs. III-E-1, III-E-2, and III-E-3.

The subjects were photographed from the front, back and side while being vibrated at each of the amplitude frequency combinations shown above. The subjects assumed normal erect posture and were requested to try to maintain normal muscular tone during the vibrations. Additional side view photographs were taken while the subjects assumed the standing defensive positions they deemed best protected them from the stress of the vibrations. Photographs were taken from a fixed point (approximately 30 feet from subject) with a Leica camera with 13.5 cm. focal length lens. Exposure times were varied but were sufficiently long to include at least one complete vibration cycle of the shake table. Two sources of illumination were used: (1) a 350-watt flood lamp, 15 feet from subject at an angle of approximately 15 degrees to line of sight of camera; (a General Radio Strobolume located next to the flood light triggered from the table to flash twice each cycle at points 180 degrees apart.) A reference mark dot on the table allowed the trigger protractor to be set to fire the strobe light at the neutral points of the table excursion.

The photographic settings of the arrangement were such that the negative of the photographs of the table spot showed a blurred dark line with a darker spot in the center. The blurred line shows the excursion of the table and is the result of the spot being illuminated by flood light for the complete exposure time. The center spot is from the exposure of at least two flashes of the strobe light during the exposure. The spots on the subject's skin show the same blurred line and center spot when the subject's spot and the table spot are vibrating in phase. When the subject spot is not vibrating in phase with the table, two spots show on the blurred line. The distance between the spots divided by the length of the blurred line is the sine of the phase angle between the subject's spot and the table. When the two spots are at the end of the blurred line, the phase angle is 90 or 180 degrees.

The negatives were projected (1/2 actual subject's size) onto a frosted glass type (Polacoat) screen.

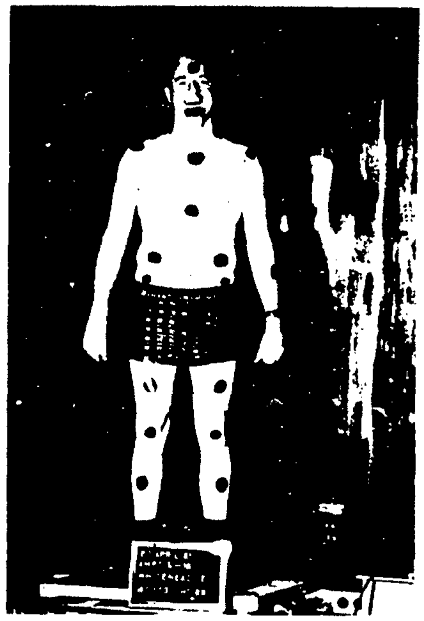


Fig. III-E-1

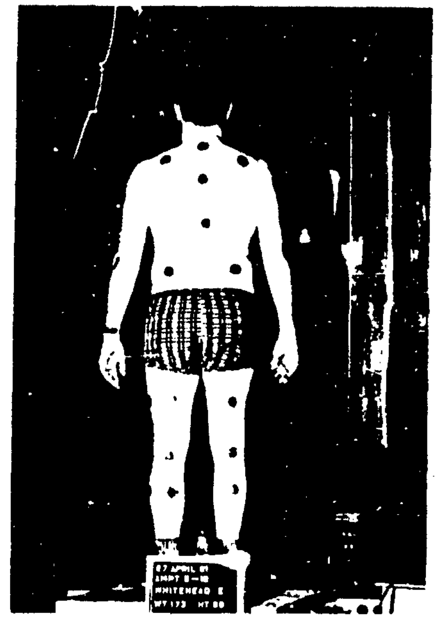


Fig. III-E-2

Fig. III-E-3

Measurements were scaled from the projection (actual x 2) and the following information obtained:

(1) Length of blurred line.

This is total excursion (double amplitude) of subject spot.

(2) Phase angle.

(3) Angle of blurred line from vertical right, left, front or back, re-lower end of line.

(4) Note if blurred line was different from a straight line. (Often elliptic.)

It developed that using the above criteria, certain of the spots were difficult or impossible to interpret. Stereo photos of one subject revealed vibration in three planes. This generally permitted interpolation of the other two dimensional negatives.

3. Experimental Protocol

All subjects received physical medical examinations before participating in the experiment.

Each subject reported the amount and general body location of discomfort at each vibration intensity.

An experimental session for each subject included weighing subject, marking subject's body, taking reference pictures from front, back and side at zero frequency, taking experimental pictures at each frequency at fixed amplitude from front, back, side and side with subject in defensive attitude, taking reaction data, removing markings. Five sessions were required for each subject, one session each week at a different amplitude. The amplitude session order was 3/16", 1/16", 5/16", 4/16", 2/16".

The choice of body sites for marking was arbitrarily made on the following basis:

(a) At least one spot for each major portion of the body.

(b) Spots over bony structures.

(c) Spots on fleshy parts.

(d) Spots on back to correspond in general with spots on front.

4. Tentative Findings

(1) A vertical forcing vibration may produce three dimensional vibration of the surface of the skin of the standing human subject.

(2) The vibration may be linear, circular, or ellipitical.

(3) The upper end of the axis of vibration of similar bilateral points is outward and away from the body.

(4) The vibration may be, at certain frequencies, almost normal to the line of vertical forcing vibration.

(5) The resonant frequency for the body is about 5 CPS. The torso, shoulders, head, thighs, and legs resonate in this order with a range of approximately 4 to 7 CPS.

(6) The onset of resonance is fast with both phase and amplitude manifestations occurring generally with 2 CPS.

(7) The ratio of body point amplitude to table amplitude at resonance of points over adipose tissue may exceed 4.

(8) At higher frequencies studied, the ratio of body-point amplitude to table amplitude of most points is less than 1 and approaches zero.

(9) Near resonance there appears to be a wavering instability of phase angle and amplitude of certain body points.

(10) Vibration variation between subjects is small.

(11) Some body points other than those marked can be analyzed. This suggests the possibility of at least partial direct application to x-ray techniques without internal marking.

(12) Stero photographic analy-is is indicated for future study.

We acknowledge with thanks the cooperation of Dr. Charles Billings as Medical Consultant and Professor Donald Mathews for subject procurement.

F. OCCUPATIONAL RAYNAUD'S PHENOMENA DUE TO VIBRATING TOOLS

Jones (20) rev wed the world literature on hand injury due to vibrating tools and .owed that the most frequently described lesion is a Raynauds-Syndrome-like vascular change in the hands of certain power tool users. However, most of the descriptions of this phenomenon appeared early in this century, described the occurrence primarily in mines and quarries in areas which are climatically cold, and it has never to our knowledge been described as occurring in hot mines even when similar or identical tools are used on equally hard rock. Udel, et al. (33) could not find the disease in the U. S. in 1960 nor could Jones or Lerner (21) find it in riveters of long experience in Columbus, Ohio .

In 1960 Dr. Norman Williams, Saskatchewan Department of Health, (25) described the disease in 11 men working in cold wet uranium mines in northern Saskatchewan (59°20'N). In June of 1961 we accepted Dr. Williams' generous invitation to see these cases and to study the mine operation in which they occur.

In the mines studied there are approximately 300 underground drillers and there is a fairly large labor turn over. Of the nine cases with positive history of this phenomenon seen by us in 1961 only two were previously described by Dr. Williams. The others seen by him had either migrated to other jobs or were on leave.

All of the nine seen by us give a history of working as a driller in hard-rock mines of from 4 to 17 years with an average exposure of 10 years. Their ages ranged from 27 - 42 years. All had worked in cold climates of northern Canada or Scandinavia all their lives, and all were using the jack-leg drill as described by Dr. Williams. They represent only about 3% of a working population whose average to this specific drill, to cold climates, and to hard-rock mines is as great or greater than the average of those affected. Seven of the nine smoke, but none excessively, and such checking as we could do both in conversations with people and in tobacco sales, indicates that the habits of the affected group does not differ significantly from the others.

Mine supervisors think that perhaps the affected group are more intense men who "fight" the tool more than others in their efforts to get more incentive-pay bonuses and that probably they are innately less dexterous and mechanically skillful than many of their colleagues.

The history usually given is that after several years of exposure to Jack-leg drilling one or two fingers of one hand begin to go dead while working. This apparently is noticed first when doing overhead work. Months later the whole hand becomes involved. Finally, especially in the overhead drilling, they say their arms become "dead". They soon

find that any event which causes body cooling will precipitate an attack whether or not they are drilling and they must take special precautions to prevent the sensation of being cold.

The "attack" is locally called white dead hands. Rather abruptly the fingers will become white, anesthetic, and useless. In less severe situations the hands may become numb and cyanotic (blue) and they go through the blue stage on re-warming. Recovery takes about an hour. No permanent change in the warmed hands has been noted by any worker, except that they are weak. On examination of the hands of the men who have these complaints one can see no abnormalities. They are strong and the sensations of light touch, pin prick, vibration and heat or cold appear to be normal. Pulses are readily felt and skin temperatures are normal, however, they rewarm very slowly after cooling.

When these hands are immersed in ice water one notes two important phenomena not made clear by previous literature on the subject as follows:

1. In a warm room with a warm body, ice water immersion of the hands up to 10 or 15 minutes often will <u>not</u> reproduce the "white hand" attack.

2. These hands are not normal in that the men can stand far longer exposure either to ice water immersion or to laying their hands on a block of ice than can the average person or other miners who don't have the syndrome. These hands do not hurt badly when immersed in ice water for 5, 10, or sometimes 15 minutes.

3. The third thing learned in this study was brought to our attention by two miners who wanted to prove they really had the disorder. Whole-body cooling will percipitate an attack promptly. (A two-minute swim in water of 50° F and then standing for one minute in a cool breeze (55° F 10 mph).)

In Figs. III-F-1 and III-F-2 are shown subject W.J.D. before his swim and after. The vascular cut-off is at the arcuate artery of the palm from which the digital arteries arise. The fingers were dead white and totally anesthetic. He could move them freely but could not grip an object and hold it unless watching what he did. Figure III-F-3 show the cyanotic response of a less severe attack in subject E.W. (He was watching a ball game on a cool evening (55° F).) Other subjects refused to be dunked in the lake, but all volunteered that to swim or go fishing even in the summer was not possible for them because it always produced an attack.

A 10th subject gave a less convincing story, could not stand his hands being in ice water for more than three minutes and swims and water skiis regularly. We decided he did not yet have the disorder.

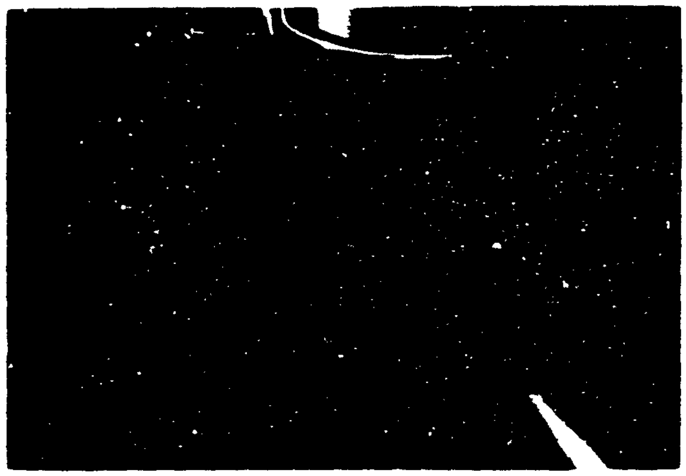


Fig. III-F-1. Subject W.D. Back of Hands Before Body Cooling

Fig. III-F-2. Subject W.D. Back of Hands After Whole Body Cooling. Note paleness of fingers.

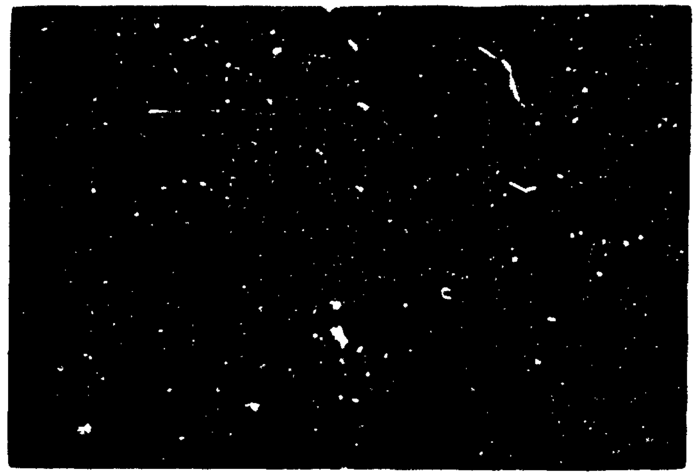


Fig. III-F-3. Subject W.D. Palm of Hands After Whole Body Cooling. Note paleness of fingers.

Fig. III-F-4. Subject E.W. Palm of Hands After Whole Body Cooling. Note cyanosis, especially left thumb.

Dr. Williams and his colleagues discuss the vibration characteristics of the tools used and the climatic characteristics of the work areas. (35) Great emphasis is put on the hazard of the Jack-leg drill versus other drills plus the possibility of the effects of a moderate amount of heat in one mine (where the disorder is either not present or less conspicuous) as compared with the other. Actually the population at risk underground is considerably smaller at Gunar Mine and the duration of exposure underground to drilling which includes overhead work is so small as to make possible no cases yet seen on a purely random basis.

Personal communication from another Canadian source indicates that this phenomenon may also exist in metal chippers in a warmed building in Ontario. We have not seen these cases as yet.

Conclusion

Raynaud's phenomenon of the hand in hard-rock drillers in a cold climate still occurs. Perhaps too much emphasis has been placed on the hands in investigating this problem and not enough on the stellate ganglion and central nervous system.

We can find no case in men who are free of overhead work. There is no evidence that exposure to ionizing radiation is contributory in these cases. Studies of the transmission of vibration through the arms, shoulder, and neck when using a drill on the ceiling are contemplated. Attempts are being made to get one or more of the cases to come to this center for angiography and other studies.

G. DETECTION, RECOGNITION AND IDENTIFICATION OF VISUAL FORMS AS A FUNCTION OF TARGET SIZE AND WHOLE-BODY VIBRATION

In the past year one cooperative project was undertaken with the Laboratory of Aviation Psychology. Mr. J. E. Donaldson, a graduate student, and Dr. George Briggs, director, proposed the following study, and the personnel of this laboratory provided the vibration environment. Mr. Donaldson's thesis is summarized below.

The purpose of this study was to determine how target size and whole-body vibration influenced man's ability to detect, recognize, and identify visual forms.

Three subjects served under all 12 conditions obtained by combining factorially two vibration frequencies, two vibration amplitudes, and three target sizes. The stimuli, eight visual targets representing the front and side view of military tank type vehicles, were randomly projected, one at a time, on a ground glass screen at a rate controlled by the subject's responses. Subjects viewed the display for one second while being vibrated on a mechanical "shake-table" at intensities similar to wheeled and tracked vehicle vibration. Three response categories were used: (a) "yes-no", to indicate detection or no detection (b) team color or tank number, to indicate recognition; and (c) team color and tank number, to indicate absolute identification. The subject's performance was measured in terms of the amount of volts required to perform each of the three visual tasks. These values were then used to compute a 50% detection, 75% recognition, and a 90% identification threshold.

The results indicated that of the three variables studied only target size differentially influenced performance. Specifically, the optimum condition for visibility and legibility occurred when the targets were greater than or equal to 36 minutes of visual angle.

The major implications of these findings for operational use are (a) in a situation where the human operator is subjected to low frequency, high amplitude whole-body vibration, increased legibility of visual forms may be attained when the target is about 36 minutes of visual angle in size; (b) if the situation imposes any restrictions on attaining this target size, then increased contrast values must be used if the target is to be recognized or identified; and (c) as the task requirements imposed on the human operator increase in difficulty and/or specificity, the figure-ground contrast must be increased.

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APPENDIX A - HUMAN PSYCHOMOTOR PERFORMANCE DURING PROLONGED VERTICAL VIBRATION

Allen Duane Catterson

APPENDIX B - OXYGEN CONSUMPTION DURING HUMAN VIBRATION EXPOSURE

John V. Gaeuman

APPENDIX A

HUMAN PSYCHOMOTOR PERFORMANCE DURING PROLONGED VERTICAL VIBRATION

CHAPTER I

INTRODUCTION

The occurrence of whole body vibration as a potentially significant stress in the realm of human environment has only become an important consideration since the advent of the industrial revolution. During the twentieth century, machinery has become more and more a common place feature of society. This has resulted in an increasingly large number of people being subjected to whole body vibration of varying characteristics for ever increasing periods of time. Concern over the possible harmful implications of this increasingly frequent exposure to vibration toward the physiologic integrity of humans so exposed, led scientists to begin the investigation of whole body vibration, considered as an environmental stress, in the later 1930's (1, 2, 14). During the past twenty-five years, a number of investigators have recorded observations on a variety of different aspects of the problem of the effects of vibration on human beings. Gradually, a considerable body of knowledge has been accumulated concerning the amplitude and frequency range within which vibration is transmitted to whole body movements (8, 19), the threshold of conscious perception (9, 14), the physical structure (2, 4, 5), subjective tolerance limits (7, 15, 17), effects on task performance and other physiological and psychological effects of vibrational force upon human subjects (10, 12, 13, 16).

The nature of the motion imparted by vibrational force, along with the extremely complex physical responses of the vibrating human organism have combined to make the direct measurement of physical and physiologic changes a highly complicated and difficult problem to solve (6). The difficulty in obtaining good reliable data, particularly on the physiologic status of vital organ systems during vibration, has proved a major stumbling block in establishing safety criteria for human exposure. Accordingly, limits of vibration tolerance which have been tentatively set to date, have been based on the degree of discomfort experienced by subjects exposed to varying levels of vibration, and subjective estimates of levels at which physical injury might occur to humans (7, 10, 15, 17).

In the absence of reliable physiologic data, other methods of assaying the effective severity of a given vibration exposure on the functional integrity of a human have been sought. One such method is the measurement of the level of proficiency of a human operator performing a complex psychomotor task while exposed to vibration as varying levels of severity. In the approach, the assumption is made that a decrement in operator performance of a standard task is a measure of the overall severity of a given vibration exposure. Human performance of a tracking task during vibration has been the subject of four previous studies which are briefly reviewed below.

Schmitz, Simon, and Radke reported on studies conducted at the Bostrom Research Laboratories (20, 21, 22) in which subjects controlled a moving pattern, displayed on a static oscilloscope, by means of a steering wheel and foot pedals. The subjects were seated, unrestrained, on a non-damping wooden chair, and experienced vertical vibration at 2-1/2 and 3-1/2 cycles per second at each of two amplitudes, which provided peak "g" accelerations of 0.15, 0.18, 0.30, and 0.35 g's. The duration of vibration was 90 minutes at each exposure. Significant decrements in performance of this tracking task were noted in these subjects and were related to the intensity of vibration exposure by the authors.

A second tracking task performance study was reported by Gorril and Snyder from the Boeing Aircraft Company laboratories (11). In this instance, the tracking task consisted of two randomly moving signals displayed as light pips moving in two planes on the face of a statically-mounted oscilloscope. These were controlled by means of a standard aircraft control column and wheel arrangement by restrained subjects seated on a standard B-47 aircraft seat. Vertical vibration was employed over a frequency range of 4-30 cycles per second. A maximum amplitude of 0.3 inch was used, and the duration of trials was 2-3/4 minutes. The subjects were restrained by a standard lap belt and shoulder harness. Significant decrements in performance were observed at 15 cycles per second and 1-1/2 g's peak acceleration. At vibration frequencies below 15 cycles per second and acceleration levels below 1.1 "g", little difference in performance was observed.

A third study of the effect of whole body vibration on the ability of humans to perform a tracking task was made by Mozell and White (18) at the U. S. Naval Aviation Medical Acceleration Laboratory. The subjects' task was to control pitch and yaw motion of a light bar displayed on the face of a statically-mounted oscilloscope. Control was accomplished by the use of an aircraft control stick mounted on the vibration table. The subjects were seated in a PBY bucket seat, restrained by a shoulder harness and lap belt, and vibrated for two-minute periods at four different frequencies and each of three amplitudes. The displacements used were 0.05, 0.01, and 0.16 inch (double amplitude). No significant effect was found on tracking ability in this study, regardless of frequency of vibration employed. It is noteworthy that the greatest displacement used was 0.16 inch, or 0.08 inch amplitude.

The fourth study of human performance of a tracking task under vibration was reported by Fraser (6) and was performed at The Ohio State University. In this study, vibration in three separate planes, vertical, horizontal-tranverse and horizontal-longitudinal was employed. Subjects were vibrated at all combinations of four frequencies and four different amplitudes in each of these three planes. The amplitudes were 0.063, 0.132, 0.191, and 0.246 inch. The frequencies were 2, 4, 7, and 12 cycles per second. The tracking task consisted of a light signal moving over a two-dimensional display board which was mounted on a shake table and vibrated along with the subject. Subjects were required to

control the light position by the use of a control stick for 58-1/2 second time intervals while seated, unrestrained, on a non-damping wood and steel chair. Significant decrements of performance were found in the vertical and horizontal transverse planes only. When these significant performance decrements were related to change in amplitude and frequency of vibration, the results showed that changes in amplitude played a greater part in performance decrement than did changes in frequency. Specifically, Fraser's study indicated that at low amplitudes, no performance decrement occurred, regardless of the plane of vibration or frequency employed. As amplitude was increased, however, tracking performance did deteriorate in a manner consistent with the severity of the vibration as subjectively perceived by the experimental subjects.

When the results of these four studies are viewed at face value, there appears to be little resemblance between the findings of any of the experimenters. However, if particular attention is paid to the function of amplitude in all of these studies, a noteworthy consistency appears. In each study, when the amplitude of the vibration was small, no decrement in tracking task performance was demonstrated regardless of frequencies, duration, or plane of vibration employed. However, when decrements in tracking proficency were found, the amplitude, in every case, was in excess of 0.1 inch. From this fact, it appears likely that amplitude above a certain minimum level may be controlling factor in determining the severity of mechanical vibration as it affects the ability of human operators to perform a psychomotor tracking task in a vibrating field. To further study this possibility, the following hypotheses were proposed:

1. The ability of human operators to perform a sensitive two dimensional psychomotor tracking task while experiencing mechancial vibration in the vertical plane is inversely related to the overall severity of the vibration as perceived by the individual human operator.

2. A threshold amplitude exists somewhere on the order of magnitude of 0.1 inch, below which mechnical vibration in the vertical plane will not affect the ability of human operators to perform this tracking task regardless of the intensity of vibration considered as a function of frequency.

The following experiment was then carried out to test the validity of these hypotheses.

CHAPTER II

EQUIPMENT AND METHODS

Five subjects were selected for this study from a group of volunteers, all of whom were graduate students in the Department of Physical Education at The Ohio State University. Each volunteer was medically evaluated prior to his participation in the experiment. This evaluation included, in addition to a medical history and clinical physical examination, a chest X-ray, an electrocardiogram, an upright X-ray of the abdomen, and a urinalysis. Table I shows the height, weight, and ages of the five volunteers selected. None of the subjects who were used showed significant abnormalities in any of the tests employed in the medical evaluation. All were active athletes in good physical condition with better than average muscular tone and excellent coordination.

The source of vibration for this study was a mechanical shake table. The table was driven by two parallel drive shafts which were powered, through a chain driven linkage, by a 7-1/2 horsepower electric motor. The rotational force of the drive shafts was translated to an oscillation of a sine wave form by six eccentric cam bearings which joined the shake table to the drive shafts. Four of these cams were positioned so that their eccentric motion was in the vertical plane, while the remaining two were positioned to exert their eccentric oscillations in the horizontal plane. The eccentricity of each cam bearing was variable in increments of approximately 1/16 of an inch, from no displacement to an amplitude of 1/2 inch or a total displacement of 1 inch. With the horizontal cam set for no displacement, the table provided vertical vibration of amplitude depending on the amount of eccentricity established in the four vertical cams. The mechanical arrangement of the motor, drive shafts, and cam bearings in diagramed in Figure 1.

Frequency was adjusted by varying the speed of the driving motor, and was monitored with a tachometer which was attached to one of the two parallel drive shafts.

The seat, control stick, and problem display panel were all rigidly bolted to the superstructure of this vibration platform. The seat was a wooden contour chair mounted on a steel frame and was designed to have minimum damping qualities. It was built by the Bostrom Manufacturing Company.

The tracking task required the subject to control the position of a moving light on a two dimensional display board. The display board was a grey wooden panel, approximately 12 inches square which was mounted on the foward end of the shake table at an angle of 50° from the horizontal. This arrangement placed the center of the display board approximately 45 inches from the eyes of the seated subject and afforded him a comfortable view of the entire face of the board.

The problem display consisted of a central white light bulb surrounded by concentric squares of equally spaced light bulbs. Each successive square was identified by a characteristic color. There were four concentric squares filling the display panel, with the outermost square consisting of nine bulbs on each side. Each bulb was 7/16 of an inch in diameter and spacing between bulbs was 1 inch.

The tracking pattern was provided by passing the signals from two sine wave generators to this display board at right angles so that one signal swept across the board from side to side while the other swept from top to bottom over the face of the board. The electrical intersection of these two signals determined the instantaneous position of the problem. As the problem signal moved over the board, a comparater circuit and a system of relay switches held the intensity of one light constant until the electrical position of the signal moved closer to the next adjacent bulb, at which time the light was switched to that bulb. Thus, the observed appearance of the problem was that of a light moving by discrete steps from bulb to bulb about the surface of the display panel.

The amplitudes of the two sine wave generators were set so that the resultant signal just filled the display board. The frequency of one signal generator was adjusted so that exactly five cycles were completed in a 58-1/2 second time period. The frequency of the second signal generator was set to complete exactly five and one-half cycles in the same 58-1/2 second time interval. This slight difference in sine wave frequencies caused the path traced by the light to be a continually changing pattern which ranged from an excursion around the perimeter of the board through a diagonal elipse, to a straight diagonal line through the center, then through a reverse elipse, back to a full excursion about the perimeter of the board, changing to an elipse in the opposite diagonal, narrowing to a line in that diagonal, again through the center, and finally returning to a full excursion about the perimeter of the board. The problem was set to repeat an integral number of half cycles in each axis during each 58-1/2 seconds elapsed time because this time interval was a mechanically predetermined score measuring period. The problem was thus set so that the light changed position approximately every 1/2 second, and covered the entire face of the display board an integral number of times during each score sampling period.

A means of controlling the position of the light was provided through a control stick which resembled a floor mounted automobile gear shift in appearance. This stick, mounted on the superstructure of the shake table between the subject's feet, extended about to knee level and could be freely moved from side to side and to and fro in a manner similar to that of an airplane control stick. Motion of the control stick actuated two potentiometers mounted in its base at right angles, so that a variable voltage resulted which could be used to nullify the voltage fed to the display board from the sine wave generators.

In order to increase the sensitivity of the problem and prevent control of the light from being overly simple, the output from the control stick potentiometers was led through integrating amplifiers in an analog computor and thence to the input signal of the display board. Thus, the voltage applied to the problem in opposition to the signal of the sine wave generators, was the integral of stick position with respect to the amount of time the stick was held in that position.

In effect, this meant that a task operator, seeing the display problem light in the upper right hand quadrant of the board would attempt to return the light to the central neutral position by moving the stick toward his lap and to the left. There would be an initial breif lag in response, followed by an acceleration of the light toward the near, left-hand corner of the board with a tendency of the light to overshoot unless rapid fine adjustments were made by the operator.

Ideal control of the problem consisted in manipulating the control stick in such a manner as to hold the position of the problem signal close enough to the center of the board to keep the central white bulb on throughout the entire task driving period.

The control stick was actuated or disconnected from the problem circuit by means of a remote toggle switch under the control of the experiment monitor.

The degree of proficiency of an operator attempting to control the light position was measured by passing the resultant signal from the display board to an analog computor. Tracking error was scored as the integral of distance the light was away from the central, neutral position with respect to the time the light was allowed to remain at a given distance. With the subject controlling the task, error was sampled by actuating a precision timer switch wired to the analog computor. Error was then summed in the side to side and to and fro axes of the display separately, throughout a 58-1/2 second time interval, and was automatically stored in amplifiers in the computor. A mathematical expression for this error measurement is as follows:

$$E = \int_0^{58\frac{1}{2}} D\,dt$$

where E = error score, D = distance from the zero light, in terms of volts required to trip successive relays, and T = time in seconds. Error was read out from the analog computor by nulling the accrued voltage with a potentiometer which allowed recording the voltage to three digits with a negligible read-out error. Once error had been recorded in each axis, it was cleared from the computor and could be repeatedly sampled for 58-1/2 second time intervals throughout the duration of the subject's task control period.

A partition was built to enclose three sides of the shake table, thus, screening distracting laboratory activities away from the subject's vision. Illumination within the partition was provided by overhead, indirect lighting which eliminated glare or vivid shadows. Provision was made for direct visual observation of the subject during his vibration exposure through a window cut in the right wall of the partition at the head level of the seated subject. This window was covered with Kaiser "shade screen," positioned so that the small louvers of the screen reflected light from within the partition back toward the interior. With this arrangement, an observer could move freely about the area immediately outside the partition, alternately observing the subject's performance and manipulating the score sampling controls without his activities being evident or distracting to the subject participating in the experiment. At the same time, if the subject wished, he could see the outside observer by looking directly through the screened window.

An electronic two-way inter-communication system was installed between the subject's position and the experiment monitor's position outside the partition. This was necessary to provide for full verbal communication over the background noise created by the power generator for the shake table motor.

As an extra safety precaution, a vibration cut-off switch was mounted on the right hand wall of the enclosure partition, under a metal strike plate approximately 9 inches square. Tapping this strike plate activated a relay which cut off the shake table motor and stopped vibration instantaneously.

For this study, it was decided to investigate the effects of vibration at two amplitudes, combined with each of six discrete frequencies. See Table II. The two amplitudes selected were the two lowest increments of displacement of which this shake table was capable and may be seen to correspond roughly to 1/16 inch and 1/8 inch respectively. The frequencies selected were 2, 4, 6, 8, 11, and 15 cycles per second. These spanned the range of frequency at which whole body resonance has been shown to occur in vertical mechanical vibration, and provided one frequency below and one frequency well above the range of major human whole body resonance (8, 10, 12).

The subjects were required to control the tracking problem continuously for two 5 minute periods during 20 minutes of uninterrupted vibration at each combination of amplitude and frequency. The sixth through the tenth, and the sixteenth through the twentieth minutes of vibration were used as task controlling periods during each experimental run. Tracking error was measured and recorded for the second and fifth minute of each task driving period, in every instance. Each vibration session was preceded by a control period during which a subject was required to drive the tracking task for two 5 minute periods under conditions which were, as nearly as possible, identical to the circumstances of the vibration run, with the exeption of the absence of the vibrational

stress. A five minute rest period was provided between the control session and the vibration session during each experimental run.

The time profile observed during each experimental run is graphically illustrated in Figure 2.

At the beginning of the experiment, the subjects were briefed, as a group, about the general purpose of the study and about the part which they were being asked to play in the experiment. While reference to specific effects of vibration or expected symptoms was carefully avoided, the subjects were advised that they were being exposed to a type of physiologic stress about which little was known and they were asked to keep track of their own subjective reactions to vibration and to discontinue any run either by signifying a desire to stop or by simply tapping the vibration cut-off switch, at any time they experienced discomfort, pain, or any other feelings which made them doubt the safety or wisdom of continuing that particular vibration exposure.

Each of the subjects was then given one hour of training during which he learned to manipulate the tracking task with a proficiency and at a level of consistency which was later shown to remain fairly stable and characteristic for each subject throughout the duration of the study. The task was sufficiently difficult that perfect scores were never achieved. A schedule was established according to which each subject participated in two experimental runs per week until all five subjects had been exposed once to each combination of amplitude and frequency. When each subject had completed half of his vibration runs, he was given a dry run during which his tracking performance was scored throughout the entire time profile as shown in Figure 2, but, no vibration was employed during the second half of the profile. This dry run was used to measure the relative importance of the effect of repeated trials as compared to the effect of boredom and restlessness on the subject's performance during the rather extended time over which the subject was confined to the environment of the shake table.

Prior to each experimental session, and at the conclusion of each experimental run, the total error of the tracking problem was recorded with the control stick disconnected from the circuit. This provided a measure of the random variability of the problem due to alteration in the power supply which occurred from time to time, and due to aging of the tubes and other electrical components of the electric circuitry.

CHAPTER III

RESULTS

The results of this experiment will be considered in two areas as follows: subjective experiences and tracking task performance.

Each of the five subjects successfully completed the planned twenty minute exposure to every one of the twelve different levels of severity of vibration. At the lower of the two amplitudes studied, none of the five subjects reported distressing symptoms or effects from the vibration experience. At combinations of the 0.06 inches amplitude and 2 and 4 cycles per second frequency, all of the subjects found the vibration to be either a very pleasant or a boring experience. One subject fell asleep during both of these mild vibrations exposures, although, he was well rested at the beginning of each experimental run. The other four subjects spontaneously remarked on the soothing monotony of vibration at 2 and 4 cycles per second.

All of the subjects found the vibration sessions at the 0.06 inch amplitude and 6, 8, 11, and 15 cycles per second to be an exhilarating group of experiences which were only mildly uncomfortable. Two of the subjects felt that their ability to control the tracking task was moderately impaired during vibration at 6 and 8 cycles per second frequency, although, they were not informed of their scores, at this time.

Vibration at the 0.13 inch amplitude was an entirely different experience for all five subjects. The exposure at 2 cycles per second was universally recorded to be a very pleasant, relaxing experience throughout the twenty minute exposure.

Four cycles per second was exhilarating for three of the subjects, and slightly undomfortable for the remaining two. No specific pain or localized discomfort was reported by the two subjects who found this exposure unpleasant, however.

All of the subjects felt that the 6 cycle per second frequency interferred markedly with their ability to manually control the tracking task and they reported a sense of muscular fatigue and tension at the conclusion of the twenty minutes exposure. Two subjects in the group (see Table III) reported fleeting migratory muscular pains at various locations in the abdomen and lower back during the 6 cycles per second vibration. These pains were of a cramping sort and were relieved by shifting position as the vibration continued. Both of these subjects reported that no pain persisted for more than a few seconds and all discomfort ceased immediately upon termination of the vibration run.

At 8 cycles per second frequency, all five subjects reported migrating, transitory chest, abdominal and/or low back pain. This was characterized as pain of gradual onset, building steadily in intensity to the point where each subject considered discontinuing this run at one time or another, but which abated or was entirely abolished by shifting position in the chair, changing breathing pattern, or using the leg and arm muscles to damp a large proportion of the vibration for a few seconds to obtain relief.

One subject (D.C.) voluntarily terminated the 8 cycle per second run after 6-1/2 minutes of continuous vibration, due to persistent high epigastric pain. This subject was hyperventilating at a profound rate just prior to the time when he discontinued the run. He exhibited pallor, cool clammy skin, and a marked tachycardia at the time he terminated the vibration exposure, although he maintained that his pain ceased instantaneously when he stopped the shake table. The subject's respiration, pulse rate, general appearance, and blood pressure returned to normal levels within three minutes of the cessation of his vibration stress. A continuously recording non-standard electrocardiogram, which was taken on all subjects during each run, revealed no change in wave form throughout this stressful exposure. This subject repeated the 8 cycle per second, 0.13 inch vibration profile after he had completed all of the other planned vibration exposures. During his second encounter with this level of vibration, the subject again experienced moderately severe migratory abdominal pains, but felt that they were not sufficiently alarming to discontinue the run a second time.

The other four subjects gave no outward indication of distress during this run, but reported the occurrence of pains after the conclusion of the twenty minute profile. The subjects were unable to localize the pains which they experienced with any degree of precision. The most frequently reported position of pain perception was in the upper anterior abdominal wall along the costal margin. The chest pain reported was all anterior and was though by all of subjects, to be located in the thoracic wall rather than deep in the chest. Back pain was reported by three subjects and was localized to the paravertebral musculature in the lumbar region of the back. The only post vibration effect reported by the subjects was vague sense of fatigue which they all equated with that felt after mild physical exertion for a similar period of time.

At 11 and 15 cycles per second frequency, the subjects complained of the same transitory trunk pains. The occurrence was less consistent and there appeared to be a correlation between frequency of vibration in cycles per second and the occurrence of trunk pain, related to the height and weight of the individual subjects. That is, the shortest lightest subject found vibration to be barely tolerable at 8 cycles per second and much less uncomfortable at 11 and 15 cycles per second, while the three subjects who were intermediate in height and weight found vibration at 8 and 11 cycles per second to be subjectively the most severe, and the tallest, heaviest subject in the group was alone in his subjective

impression that the 15 cycle per second frequency was the most severe. This tallest, heaviest subject (R.C.) experienced slight pain at 6 cycles per second, relatively little discomfort at 8 cycles per second, and increasingly severe discomfort at 11 and 15 cycles per second. He was generally unimpressed with vibration as a stressful experience until he was exposed to 15 cycles per second at 0.13 inch amplitude. He reported that he then felt marked discomfort for the first time.

The significant subjective complaints of the subjects are summarized in Table III.

At the conclusion of the experiment, the mean value of the observed uncontrolled problem scores from all runs was arbituarily selected as the standard uncotrolled problem score. All observed tracking scores were then corrected to this standard problem score by multiplying the scores recorded during each run by the ratio of the standard problem score divided by the observed uncontrolled problem score. This correction reduced the effect of random variability of the tracking problem on comparisons between scores observed at different times. Subject control scores for each run were obtained by calculating the arithmetic mean of the four error scores recorded during the twenty minute control period. The mean error score during each five minute task driving period under vibration was similarly calculated for each subject during each run. For the non-vibrating dry run session, the mean error score for each of the four 5-minute task driving periods was calculated and recorded separately. See Table IV. With the exception of this dry run session, the mean control period score obtained for each subject was taken as a measure of that subject's proficiency during each experimental run. The mean control score was accordingly subtracted from vibration error scores as obtained for each task driving period of vibration. If the error score obtained during a vibration period, was less than the control error score, a negative value was recorded as net error score for the subject. The net error scores were then pooled for all five subjects at each combination of frequency and amplitude of vibration. The mean net error scores, representing the average change in tracking proficiency which was observed at each combination of frequency and amplitude, are recorded in Table V.

These changes in tracking proficiency were subjected to an analysis of variance to test for significant differences between frequencies alone, between the interaction of amplitude and frequency at each level of intensity of vibration, and between early and late driving periods during each condition of vibration.

The summary of the analysis of variance is shown in Table VI. As may be seen in the right hand column of this table, changes in frequency are associated with significant changes in error score at the one per cent level as are changes in the interaction between amplitude and frequency, while changes in amplitude are associated with changes in score at a probability level of far less than .01 per cent. Differences between the early and late driving time period were not significant at these levels of vibration (3).

The average change in tracking proficiency as measured for each combination of frequency and amplitude is shown graphically in Figure 3.

CHAPTER IV

DISCUSSION

In reviewing the data collected during this experiment, two facts emerged with great consistency and would thus appear to warrant special consideration.

First of all, the subjective complaints reported by the subjects during the experimental exposures are in general agreement with the findings of other investigators who have measured subjective human tolerance to vertical sinusoidal vibration (7, 15, 17). The consistency with which these complaints were elicited at combinations of the 0.13 inch amplitude and 5, 8, and 11 cycles per second frequency, indicates that subjects in this study were stressed at levels very near their psychological tolerance to vibration during the study. It would seem noteworthy then, that all five of these subjects were able to perform this sensitive two-dimensional tracking task in a constructive manner even while on the verge of discontinuing an experimental run due to general discomfort. Moreover, during combinations of amplitude and frequency which were subjectively the most severe, individual subjects generally showed an improvement in tracking performance by the end of a twenty minute exposure to vibration as compared to performance early in the period of vibration.

Each of the subjects attributed this ability to perform the tracking task during what was to him severe vibration, to the fact that he was free to accommodate to his environment through changes in position, posture, and through the use of conscious damping of the vibration by adjustments in skeletal muscular tone.

This subjective impression on the part of the individual subjects was borne out by observations of the monitors of the experiment who noticed a continual adjustment in posture and position in the chair by each subject during the severe vibration. This evidence of natural accommodation to vibrational stress by the unrestrained subjects raises the suggestion that at these levels of amplitude and frequency, unrestrained human operators in a vibrating field may enjoy advantages of natural protective mechanisms which are not available to human operators, tightly coupled to their seat by safety harnesses or other restraining apparatus.

The second significant fact to emerge from these data is the unquestionable importance of amplitude in defining the effective severity of any given level of mechanical vibration. As is shown in Table II where the peak accelerations of the difference combinations of amplitude and frequency are tabulated, several combinations of the frequencies used with the 0.06-inch amplitude provide accelerations which exceed those which result from combinations of the lower frequencies with the 0.13-inch amplitude. However, when tracking performance is considered,

it may be seen from the graph in Figure 3, that at the 0.06-inch amplitude, tracking proficiency was never adversely affected by vibration, regardless of the frequency of that vibration. Conversely, at the 0.13-inch amplitude, tracking proficiency was seen to deteriorate, relative to the non-vibrating state at all frequencies.

The absolute difference between the amplitudes used in this study is again dramatically demonstrated by the results of the analysis of variance carried out on the data. Here the significance of the differences between amplitudes literally overwhelms the level of significance found related to difference between the other sources of variance tested.

This finding challenges the validity of previously proposed empiric equations relating the effective severity of vibration levels to peak accelerations or peak velocities.

Furthermore, in the previous experiments, where human tracking performance was measured in relation to varying levels of mechanical vibration, those investigators who employed very low amplitudes in the neighborhood of 0.1-inch or less found no decrement in tracking performance, while those investigators who used amplitudes greater than a value on the order of 0.1-inch consistently found decrements in tracking performance (6, 11, 18, 20, 21, 22).

CHAPTER V

CONCLUSIONS

Three specific conclusions may be drawn from the results of this experiment as follows:

1. Under the conditions of whole body mechanical vibration which were observed in this study, human performance of a sensitive, two-dimensional light tracking task is a useful indicator of the effective severity of vibration.

2. Human operators are capable of performing this tracking task in a satisfactory manner at levels of severity of vibration which approach subjective psychological tolerance levels.

3. Deterioration in proficiency of this tracking task is primarily dependent on the amplitude of the vibration in that a threshold amplitude exists below which tracking proficiency is not adversely affected regardless of the frequency of vibration employed.

CHAPTER VI

SUMMARY

This study was carried out to clarify the relative importance of changes in frequency compared to changes in amplitude in determining the severity of whole body vibration in the vertical plane. The ability of human operators to perform a difficult, two-dimensional tracking task at rest, and while vibrating, was compared as a measure of the effective severity of a given level of vibration.

Five volunteer subjects were each exposed to twelve levels of vibration, determined by six descrete frequencies and two amplitudes. Changes in proficiency of performance of the tracking task were electronically measured, and pooled results from the five subjects were subjected to an analysis of variance. Changes in performance were tested as they related to changes in frequency, changes in amplitude, changes in the interacting combinations of frequency and amplitude, and changes in duration of the vibration exposure.

Results of the analysis of variance showed that performance of the tracking task did change significantly as either frequency, amplitude, or both varied. However, the significance of changes in task performance as related to changes in amplitude of vibration so overshadowed the level of significance of changes in performance when related to any other source of variance, as to indicate that amplitude is the variable of greatest importance in defining the severity of vibration under the conditions of this study.

It was felt noteworthy that all of these subjects were able to carry out the tracking task for the required time periods throughout each level of vibration severity, even though the most severe levels approximated subjective tolerance limits to vibration. Moreover, the tracking proficiency at the end of twenty minutes of continuous vibration was as accurate as that found after only five minutes of vibration at each level of severity.

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TABLE I

AGE, HEIGHT, AND WEIGHT OF VIBRATION SUBJECTS

Subject	Age (years)	Height (inches)	Weight (pounds)
D.C.	21	66-1/2	138
J.K.	25	70	155-3/4
R.B.	22	69-3/4	157
H.M.	34	70	175
R.C.	22	72-1/2	177

TABLE II

VIBRATION LEVELS

Amplitude (Inches)	Frequency (Cycles Per Second)	Peak Accelcration Values (G's)
A_1 - 0.06	f_1 - 2	0.03
(D.A. - 0.13)	f_2 - 4	0.10
	f_3 - 6	0.23
	f_4 - 8	0.41
	f_5 - 11	0.77
	f_6 - 15	1.44
A_2 - 0.13	f_1 - 2	0.05
(D.A. - 0.26)	f_2 - 4	0.20
	f_3 - 6	0.46
	f_4 - 8	0.82
	f_5 - 11	1.55
	f_6 - 15	2.88

Note. Amplitudes are nominal values representing the vertical excursion of the shake table platform in either direction from its mid-position. They were produced by setting the vertical cams to precisely machined increments of eccentricity. The cam settings used were 0.048 in. and 0.115 in.

TABLE III

OCCURRENCE OF PAIN IN INDIVIDUAL SUBJECTS AT VARYING LEVELS OF VIBRATION

Subject	Vibration Level					
	Amplitude - 0.06 in.					
	2cps	4cps	6cps	8cps	11cps	15cps
D.C.						
J.K.					a	
R.B.					c	c,b
H.M.					a	
R.C.					a	
	Amplitude - 0.13 in.					
	2cps	4cps	6cps	8cps	11cps	15cps
D.C.			b	a(x2)	a	
J.K.				a	a,c,b	
R.B.				a	a,b	
H.M.				a	a	
R.C.			a	a,c	a	a,c

Key: a - abdominal pain.
c - chest pain.
b - back pain.

TABLE IV

INDIVIDUAL SUBJECT PERFORMANCE SCORES DURING EACH TASK DRIVING PERIOD OF THE "DRY RUN" SESSION

Driving Period	Subject				
	H.M.	D.B.	D.C.	J.K.	B.C.
1	343	597	687	519	662
2	360	593	818	570	711
3	343	553	613	512	772
4	330	549	645	454	645

TABLE V

NET TRACKING ERRORS: VIBRATING SCORES--CONTROL SCORES AT EACH LEVEL OF VIBRATION: (MEAN OF FIVE SUBJECTS)

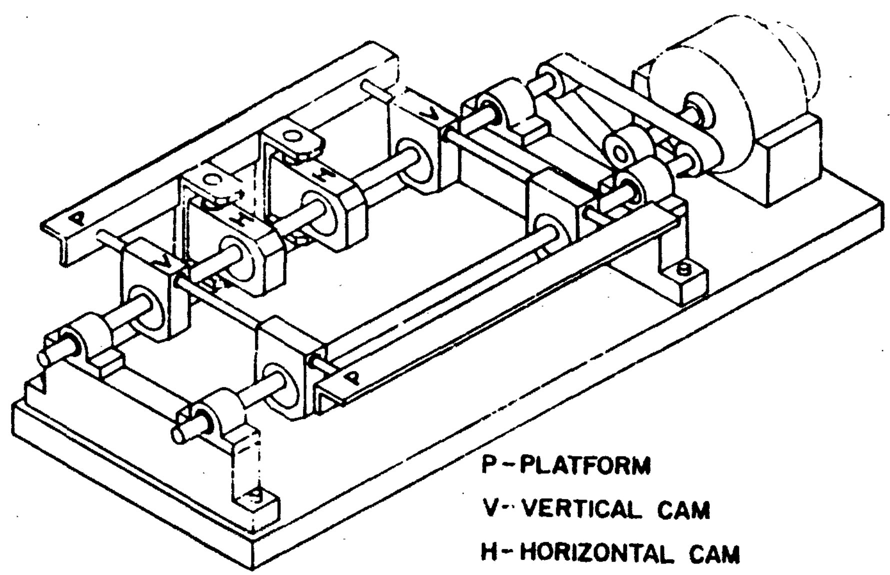
Amplitude	Frequency	Net Error per Time Period	
		5-10 min.	15-20 min.
0.06"	2 cps	- 66	- 66
	4 cps	- 42	- 51
	6 cps	- 72	- 72
	8 cps	- 40	- 57
	11 cps	- 80	-112
	15 cps	- 54	- 63
0.13"	2 cps	+ 25	+ 46
	4 cps	- 18	+ 2
	6 cps	+ 44	+ 48
	8 cps	+106	+ 78
	11 cps	+ 26	+ 39
	15 cps	+ 30	- 5

TABLE VI

SUMMARY OF ANALYSIS OF VARIANCE

Source of Variance	Degrees of Freedom	Sum of Squares	Mean Squares	"F"	d.f.	p.
Between Frequencies	5	7,396	1,479	7.99	n_1, 5 n_2,12	0.01
Between the Interaction of Amplitude and Frequency	5	7,401	1,480		n_1, 5 n_2,12	0.01
Between Amplitudes	1	59,601	59,601	322.	n_1, 1 n_2,12	< 0.0001
Between Time Periods	1	216	216	1.17	n_1, 1 n_2,11	> 0.10
Error	11	2,309	185			
Total	23	76,653				

FIG. I SHAKE TABLE (DIAGRAMMATIC)



P - PLATFORM
V - VERTICAL CAM
H - HORIZONTAL CAM

FIG. 2 TIME PROFILE OF A SINGLE RUN

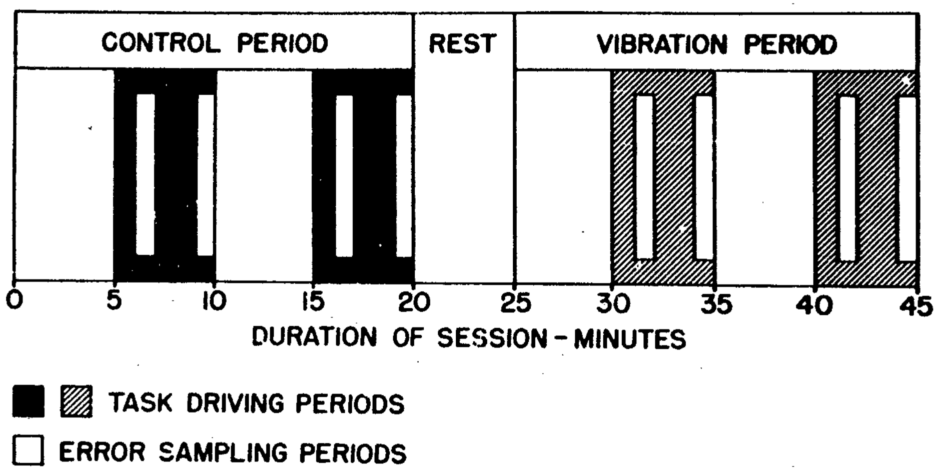
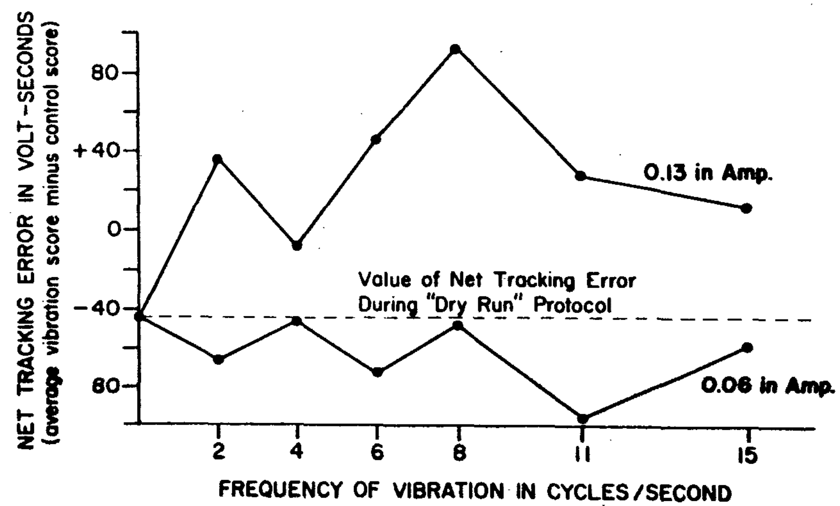


FIG. 3 NET TRACKING TASK ERROR VERSUS LEVEL OF VIBRATION

(MEAN VALUES FROM PERFORMANCE OF FIVE SUBJECTS)



APPENDIX B

OXYGEN CONSUMPTION DURING HUMAN VIBRATION EXPOSURE

Introduction

Either by reason or observation, it is apparent that the animate subject exposed to mechanical whole body vibration does not respond merely as a blob of matter of some more-or-less elastic material. Since most whole body vibration at certain amplitudes is uncomfortable if not intolerable, the subject attempts to defend himself, if free to do so; and, it seems reasonable that this defense requires the expenditure of some amount of energy. There has been very little specific data reported in the literature quantitating the effects of vibration on this energy expenditure in the human subject. Some scattered observations have been made which suggest that there might be some significant alterations in oxygen consumption and metabolic rate. This paper deals with measurements made on oxygen consumption ($\dot{V}_{O_2}$), minute volume of respired air ($\dot{V}$), and respiratory exchange ratio (R) during vibration exposure.

Background

Loeckle[11] demonstrated an inhibition of the achilles reflex during vibration of the whole body and local vibration over the abdomen and thighs. He suggested that the reflex inhibition was due to effects on the sympa-nerves traveling along the course of the great vessels. Goldman[9] also demonstrated this in the cat, but also produced the same effect after sympathectomy, and concluded that vibration produced a periodic, synchronous stretch reflex in the in the muscles. Coermann[3] measured the patellar reflex, oxygen consumption, respiratory volume, and respitary exchange in human subjects exposed to vertical vibrations ranging from 15 to 100 cps at low amplitudes. His measurements showed a rise in muscular tension immediately after vibration commenced but that this decreased to less than normal after only a few minutes of exposure. Schaefer[14] exposed rats to daily periods of vibration on restraining boards and found them to weigh less, require more food to maintain weight, and at the same time to be less active than control animals. Studies done by Carter[1] vibrating unrestrained rats at frequencies ranging from 3 to 26 cps and amplitudes of 0.062, 0.125 and 0.25", showed an increase in oxygen consumption which was proportional to the increase in vibration stress. He also found a decrease in activity and oxygen consumption at the lowest frequencies, indicating a tranquilizing effect. Duffner and Hamilton[7] exposed human subjects to vertical sinusoidal vibrations of 2-7 cps at peak "g" levels of 0.15 and 0.35, over a period of four minutes. They measured an increase in oxygen consumption and minute volume, which occurred immediately after onset of vibration and stayed constant over the vibration period.

This study was designed to measure the effects of vertical sinusoidal vibration in human subjects over a moderately long time interval and approaching maximum tolerance limits in severity.

Methods

Four university graduate students volunteered as subjects. They were healthy young adult males in better than average physical condition. All were given a thorough medical evaluation before the experiment, including physical examination, PA chest X-ray, upright abdominal X-ray, twelve lead ECG, and urinalysis. Special attention was directed toward the detection of abnormalities of the musculo-skeletal system, the cardiovascular and renal systems. In view of the incidence of hepatitis and infectious mononucleosis in this population, history or evidence of hepatomegally or splenomegally was carefully sought. Unstable or restricted joint motion, previous back trouble, hernia plonidal sinus, vasomotor instability, congenital cardiovascular abnormalities, evidence of renal dysfunction, or history of prostatitis were other relatively common conditions considered a contraindication to experimental exposure.

The subjects were evaluated medically during the experiments, and repeat urinalysis performed after vibration exposure at frequencies of 11 and 15 cps. No incidence of protienuria or microscopic hematuria was found.

Each subject was exposed to whole body vibration for periods of 20 minutes at a time, during which expired air was collected for analysis of oxygen and carbon dioxide content. Vibration was sinusiodal in form with vertical displacement produced by a shake table mounted on cam-shafts driven by an electric motor. While frequency was easily controlled by varying motor speed, changing amplitude required readjustment of the eccentricity of the cams. Intensities used were all at 0.132-inch table amplitude (0.264 inch total vertical displacement), at frequencies of 2, 6, 8, 11 and 15 cps, representing peak "g" loads of 0.05, 0.46, 0.82, 1.55 and 2.88 respectively:

$$\text{peak } g = \frac{4 \pi A \; f^2}{(32)\;(12)}$$

g = pure units relative to 32 ft/sec/sec
A = amplitude in inches
f = frequency in cps

In general, data was collected on each subject on one run at each frequency, giving data on twenty separate runs. (One subject was exposed to two runs at 15 cps but was not exposed to 2 cps).

The subject was seated on a special undamped chair bolted to the shake table. The entire system was enclosed in a small booth to reduce distraction. Although required to maintain a seated position, the subject was unrestrained and free to assume the most comfortable posture.

Expired air was collected by adapting an Air Force type A-13A pressure-breathing mask. The two valves from the inspiratory ports were removed and one placed in the expiratory port, in place of the pressure compensated expiratory valve. The port in the supply line for the pressure compensated

valve was plugged. This produced a complete reversal of air flow through the mask. Inspiration of air back through the hose was prevented by placing a low resistance flap-valve between the mask and the collecting spirometer (see Figs. 1 and 2). It was felt that this method would allow breathing of room air and collection of expired air over a long time interval more tolerably for the subject, and would allow communication via microphone during the experiment. Expired air was sampled and analyzed from each five-minute interval during vibration and through a standard post-vibratory period of 15 minutes. Analysis was also performed on the total volume at the end of the vibration and recovery periods. In addition, each subject served as his own control for a 20-minute profile exactly duplicating the experimental period but without the vibration. This control period immediately preceded each experimental run with a five-minute rest between.

Gas analysis was performed immediately after collecting the samples, using a two-liter aliquote of each five-minute collection. Oxygen content was determined with a Beckman Model E2 Oxygen Analyzer set up for fixed volume analysis and standardized with commercial 100% oxygen and nitrogen as reference gases. Carbon dioxide analysis was done on a Beckman Model LB-1 Gas Analyzer, using a micro-analyzer chamber on remote pick-up and standardized with room air and 10% carbon dioxide.

Oxygen consumption and carbon dioxide elimination were calculated utilizing volume recordings made on a kymograph attached to the collecting spirometers. Inspiratory volumes were determined relative to the nitrogen volume:

$$\dot{V}_I = \dot{V}_E \frac{1 - (F_{CO_{2_E}} + F_{O_{2_E}})}{1 - (F_{CO_{2_I}} + F_{O_{2_I}})}$$

Room air carbon dioxide content ($F_{CO_{2_I}}$) was considered to be zero. Room oxygen percentage ($F_{O_{2_I}}$) was determined for each run. The average room air oxygen concentration for the 20 runs was 20.77% with a standard deviation of 0.15%.

Results

The over-all results are depicted in Figs. 4 through 10. The ordinate represents the actual value as per cent of change from the control value. The abscissa represents increasing frequency of vibration. Shown in the figures are the range and mean values of the four subjects. In view of the small number of subjects, who were in widely varying metabolic states in each separate run, absolute values are not readily comparable and the range was felt to be more meaningful than the standard deviation.

Fig. 4 represents the change in $\dot{V}_{O_2}$ during the total vibration period when compared with the control values.

Fig. 5 represents the change in $\dot{V}_{O_2}$ during the post-vibration recovery period when compared to the control values.

Figs. 6 and 8 relate $\dot{V}$ in the same manner to the control values. The curve in Fig. 7 is the difference between the absolute values of curves 4 and 6, and represents the change in mean $\dot{V}$ relative to $\dot{V}_{O_2}$ during vibration compared to the control relationship.

Figs. 9 and 10 represent the changes in R during the vibration and recovery periods respectively.

Table 1 summarizes the mean values presented in Figs. 4 through 10.

Table 2 tabulates the mean control values for $\dot{V}_{O_2}$, $\dot{V}$ and R for each subject and for all runs together. This table indicates the inadvisability of attempting comparison of absolute values between subjects and the mean and deviation calculated on all runs have very little meaning other than an indication of magnitude.

Table 3 lists the calculated coefficients of correlation between $\dot{V}$ and $\dot{V}_{O_2}$ and various functions of frequency.

The criterion for statistical significance between values was generally based on a "t" test confidence level of 0.05.

Discussion

The change in $\dot{V}_{O_2}$ occurring during vibration occurred almost immediately after onset of vibration and remained steady throughout the vibration period. There was found to be no significant difference between $\dot{V}_{O_2}$ during the first five minutes and the rest of the vibration period. The data on Fig. 4 show a definite linear positive correlation of $\dot{V}_{O_2}$ with respect to increasing vibratory frequency. Linear group correlation based on class intervals of 10% of change is presented in Table 3. The highest correlation found is between $\dot{V}_{O_2}$ and frequency as a direct function. Fraser[8] found highest correlation between psychomotor function impairment and " $\sqrt{f}$," and "g" has often been utilized as an attempt to measure vibration stress. Correlation between $\dot{V}_{O_2}$ and either " $\sqrt{f}$" or "g" is not quite as high as between $\dot{V}_{O_2}$ and "f" directly, but the magnitude of "r" based on any of the three functions of frequency is in the same range.

There is also indication in Fig. 4 that there may be some depression of $\dot{V}_{O_2}$ below the control value at 2 cps, as suggested by the studies of Carter[1] mentioned previously, although with this number of observations statistical validity cannot be demonstrated.

In Fig. 5, it appears that in the recovery period, there is a consistantly lower $\dot{V}_{O_2}$ when compared with the control value, suggesting a relative hypermetabolic state during the control period. This is reflected in the somewhat elevated absolute $\dot{V}_{O_2}$ shown in Table 2. The question arises as to whether there might be a continued fall-off of $\dot{V}_{O_2}$ over the time of each individual run which is masked by the effects of vibration. Comparing the first five minute interval of the control period to the final five minutes of the control, a significant decrease in $\dot{V}_{O_2}$ over time was found in only one subject. However, this subject's recovery $\dot{V}_{O_2}$ was depressed no more than the average of all the subjects, so that the final answer to this question is not certain. The depressed values during recovery would appear to be mostly a phenomenon of relief and relaxation following the exposure to vibration. At any rate, admitting an error of this type would accentuate the changes during vibration noted above, since they are largely in the opposite direction, and would not invalidate the data.

The magnitude of $\dot{V}_{O_2}$ elevation, reaching a maximum of about 65% at 15 cps, is on the order of that which might occur during light exercise. With this degree of oxygen utilization, a significant oxygen debt would not be expected. At 15 cps, there is a 10% higher $\dot{V}_{O_2}$ during the first five minutes of the recovery when compared with the total 15 minute recovery period. This is a significant elevation. The dead space of the system adding air expired during vibration to the recovery period could result in at most about a 3% elevation during the first five minutes; thus this suggests some degree of oxygen debt. There is no significant elevation at the other frequencies. As noted in Fig. 5, there is no particular difference in magnitude of total $\dot{V}_{O_2}$ change during recovery despite the frequency of vibration.

The data in Fig. 6 show an increase in $\dot{V}$ during vibration exposure consistent with the increase in $\dot{V}_{O_2}$. However, there is a relatively greater increase in V compared with $\dot{V}_{O_2}$ at the 6 cps frequency, shown in Fig. 7. This indicates some hyperventilation at this frequency, either because of discomfort or a result of the resonance of the abdominal organ mass pumping the diaphragm. Although Coermann[4] and DuBois[6] reported lower resonance frequencies for the thoraco-abdominal system, both made measurements on supine subjects. Loeckle[11] suggested a diaphragmatic resonance of 6-10 cps, largely dominated by the liver. Guignard[10] found the maximum transmissability of vibration from seat to shoulder in seated subject to be at 5-6 cps. Diekmann[5] found that shoulder resonance in standing subjects reached a peak with a 65% amplification of vibration at 4-5 cps. On the other hand, tolerance limits largely dictated by chest and abdominal pain noted in these experiments, have also been observed in more extensive evaluations by Fraser[8] and Magid[12]. The increase in $\dot{V}$ observed by Duffner and Hamilton[7] was due to an increase in tidal volume, with a relative decrease in respiratory rate. This tendency to deepen breathing was also noted by Loeckle[11].

The 5 cps peak in $\dot{V}$ accounts for the lower, although still significant, linear correlation between $\dot{V}$ and "f" in Table 3. Again, there is no significant difference in "r" referred to any of the three functions of frequency.

In Fig. 8, a decrease in $\dot{V}$ is seen during the recovery period, which is of consistent magnitude despite the vibration exposure level. The recovery depression of V is relatively greater than that of V_{O_2}, probably as a result of relative hyperventilation during the control period.

The data presented on R in Figs. 9 and 10 are admittedly subject to a great deal of error and variability. This function is notoriously sensitive to experimental manipulation. It should be noted that the ordinate scale is one-tenth that of the preceding figures. Abnormally high ratios were obtained in all runs, which may in part reflect a hyperventilation as a result of psychological and mechancial effects of the mask and collecting system. With the arrangement of inspiring room air through the dead-space of the mask (Fig. 2), there is the probability of some carbon dioxide rebreathing. As the calculations for gas exchange were based on assuming inspiration of carbon dioxide free air, a system was devised to eliminate inspiring through this dead-space. A mouthpiece with a valve was sealed into the expiratory vent of the mask, so that room air could be inspired through the mouth and expired through the nose into the mask system (see Fig. 3). This arrangement did not affect the calculated R, but did produce a significant reduction in $\dot{V}$.,thus indicating that although rebreathing of carbon dioxide was sufficient to produce hyperventilation, other factors were more important in elevating R.

The psychological elevation of R might be expected to reduce with time over each experiment run, explaining the variable but consistently decreased R during recovery as compared with the control value. The significantly elevated values at 5 cps and to a lesser extent at 8 cps are consistent with the data on the V_{O_2} - $\dot{V}$ relationship, and confirm the observations made above. Unfortunately, carbon dioxide analysis was not available on the runs at 2 cps, so that the expected reduced R at this frequency cannot be confirmed.

Conclusion

The observations support the hypothesis that human subjects can tolerate relatively severe degrees of whole body vibration and still function[2] if they are unrestrained and free to protect themselves. This protection is apparently a function of positioning the body and by voluntary and involuntary muscular guarding to dampen the vibration and reduce the transmission of stress to the vulnerable body areas. The exact location of the vulnerable areas has not been investigated, and from subjective experience the maximum response seems to vary with the frequency between 6-11 cps depending on the individual body build. Despite the difference in frequency response, there appear to be similar types of discomfort produced in all subjects, the vibration tolerance being limited to a large extent by chest and abdominal pain.

The protective efforts induced by vibration result in an increase in metabolic activity which is strikingly reflected in the $\dot{V}_{O_2}$. At levels of 6-15 cps, near the primary and secondary body resonant points, the increase in $\dot{V}_{O_2}$ is nearly linear with increasing frequency of vibration. The magnitude of increased metabolic load resulting from this effort, being less than double that of resting controls, while not extreme, is significant; and since it must be a constant effort, it is sufficient to be a substantial contributor to fatigue in subjects exposed to vibration over extended periods. It is also evident that the increase in respiratory requirements must be considered when dealing with the problem of subjects in supplied or sealed environments.

Radke[13] suggested that 1 to 1-1/2 cps would be a desireable seat frequency for improving truck ride characteristics. While this does seem to be a pleasurable ride, there is objective evidence of a sedative and somnolent effect produced by frequencies in this range. It may be that these low frequency components are responsible for much of the subjective drowsiness occurring in persons exposed to vibrations of machinery and vehicles.

Finally, there appears to be an induced hyperventilation at 6 cps, possibly as a result of the resonance of the abdominal organ mass producing diaphragmatic pressure, or alterations in respiratory mechanics induced by physical discomfort. The quantitative effect on alveolar carbon dioxide tension cannot be accurately evaluated since a steady base-line is not evident, and it is not certain that this hyperventilation could or would be maintained sufficiently long to produce respiratory alkalosis sufficient to contribute to impaired function.

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Table 1. Per Cent Change of Respiratory Function
Frequency Compared to Control Values
Mean Value of Four Subjects

Freq., cps	Vibration			Post-vibration		
	$\dot{V}_{O_2}$	$\dot{V}$	R	$\dot{V}_{O_2}$	$\dot{V}$	R
2	-6.9	-5.1	--	-7.1	-33.2	--
6	8.4	20.6	7.3	-10.4	-31.8	-1.0
8	27.4	32.2	2.6	-8.0	-33.9	-7.4
11	36.3	32.3	-0.3	-7.9	-30.9	-2.5
15	63.4	53.8	-3.2	-4.0	-31.2	-6.0

Table 2. Control Values Mean ± Standard Deviation

Subject	Age	Height, in.	Weight, lb.	$\dot{V}_{O_2}$, cc/min.	$\dot{V}$, L/m	R
RC	22	70	153	311 ± 44	8.6 ± 1.0	1.146 ± .041
RB	22	72	178	317 ± 25	9.5 ± 0.96	1.135 ± .046
JK	26	70	155	291 ± 10	9.0 ± 0.68	1.147 ± .103
HM	34	70	175	247 ± 24	6.8 ± 0.98	1.119 ± .096
All runs				292 ± 34	8.5 ± 1.4	1.137 ± .069

Table 3. Linear Correlation Coefficients (r)

	Percent of change from control	
	$\dot{V}_{O_2}$	$\dot{V}$
f	0.92	0.64
$\sqrt{f}$	0.80	0.72
"g" ($f:f^2$)	0.85	0.67

$$r = \frac{N\Sigma fXY - \Sigma fxX\Sigma fyY}{\sqrt{[N\Sigma fxX^2 - (\Sigma fxX)^2]\,[N\Sigma fyY^2 - (\Sigma fyY)^2]}}$$

N = 20
Y = percent of change, class intervals of 10
X = function of frequency

A-13A PRESSURE-BREATHING MASK

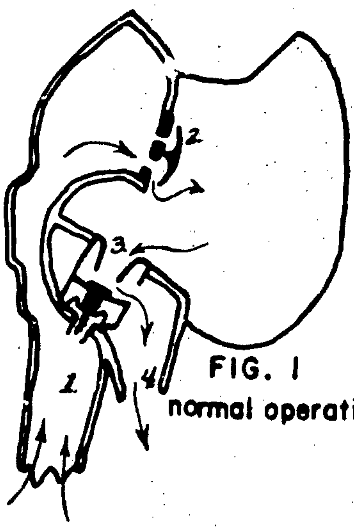

FIG. 1
normal operation

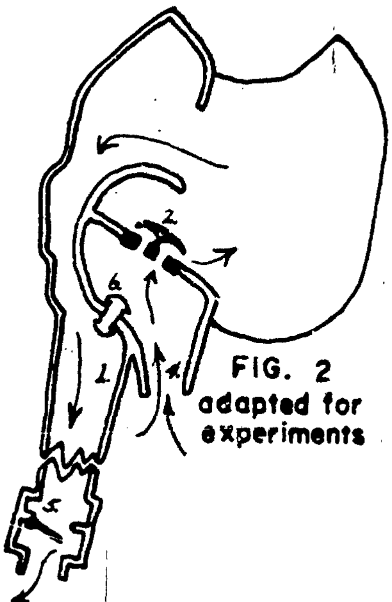

FIG. 2
adapted for
experiments

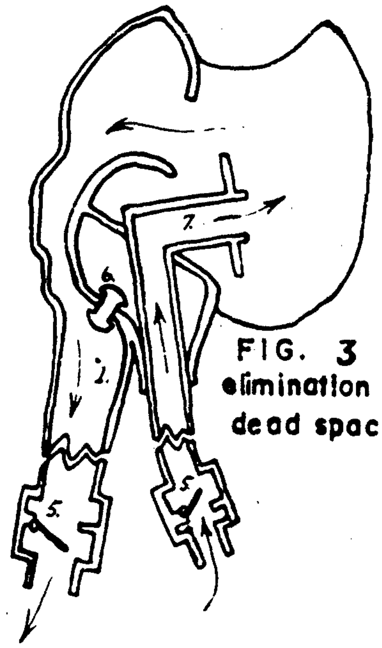

FIG. 3
elimination of
dead space

1. supply hose
2. inspiratory diaphragm valve
3. pressure compensated expiratory valve
4. expiratory vent
5. low resistence flap valve
6. plug in port
7. mouthpiece

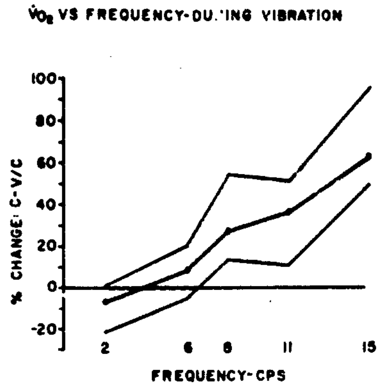

Fig. 4

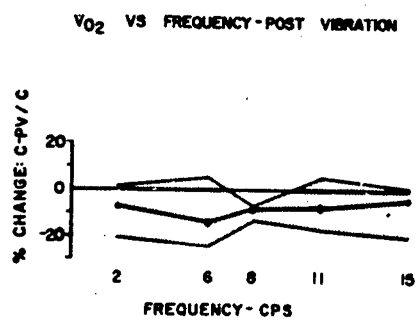

Fig. 5

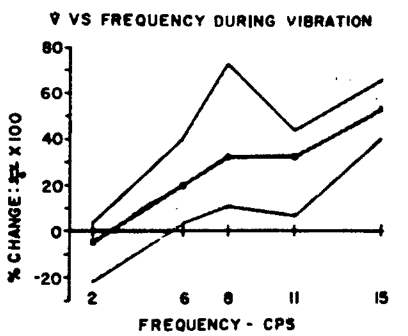

Fig. 6

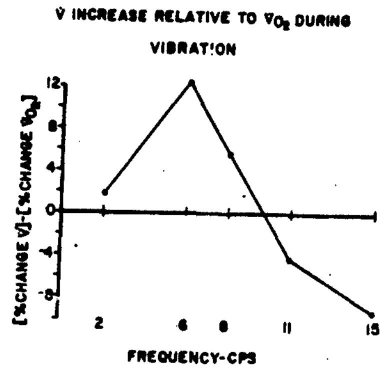
V INCREASE RELATIVE TO VO2 DURING VIBRATION
12
8
4
0
-4
-8
[%CHANGE V]-[%CHANGE VO2]
2
6
8
11
15
FREQUENCY-CPS

Fig. 7

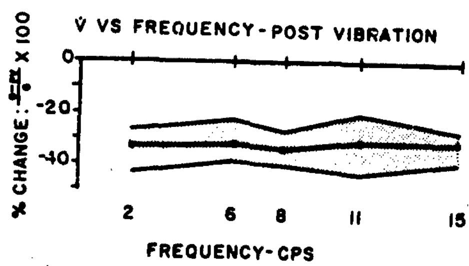
V VS FREQUENCY-POST VIBRATION
0
-20
-40
% CHANGE: X 100
2
6
8
11
15
FREQUENCY-CPS

Fig. 8

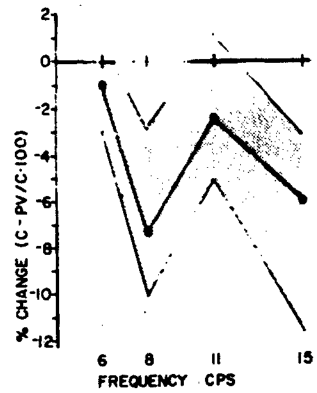
% CHANGE (C-PV/C·100)
FREQUENCY CPS

Fig. 9

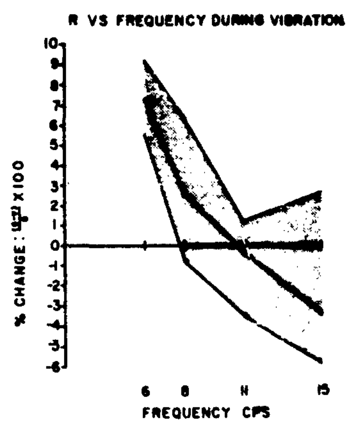
R VS FREQUENCY DURING VIBRATION
FREQUENCY CPS

Fig. 10